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THE USE OF SURFACE GEOPHYSICAL METHODS IN UNDERGROUND WATER INVESTIGATIONS

Proceedings of a Symposium

by the

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Contributions by

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INTRODUCTION

The Australian Water Resources Council arranged a seminar on "The Use of Surface Geophysical Methods in Underground Water Investigations". The seminar took place in Adelaide on 12-14 August 1975.

The purpose of the seminar was, firstly, to bridge the credibility and communications gap between geophysicists, engineers, and hydrogeologists; secondly, to indicate the possibilities and limitations of geophysical methods as applied in Australia; and thirdly, to evaluate problems in the application and use of these methods.

The aim of this Record is to make the proceedings and discussions widely available to practising geophysicists, engineers, hydrogeologists and water resource management. In editing these papers we have limited ourselves to removal, with the authors' consent, of unnecessary repetition in the discussions, and references to manufacturers and performance of equipment. Sections dealing with borehole logging operations were deleted as this subject is outside the scope of the symposium.

During the symposium seven papers were read and discussed.

Dr D.E. Leaman of the Mines Department of Tasmania covered the philosophical and practical aspects of successful geophysical exploration, going back to training in geophysics at the university level for geophysicists, geologists, and engineers. He then introduced most of the geophysical methods, dealing with their applicability and limitations in different conditions and requirements.

D.T. Currey from the Victorian State Rivers and Water Supply Commission in his paper "Geophysics and the Customer" gave his reminiscences of 15 years' contact with geophysical contract activities. The subject ranged from the salinity problems of the Riverina Plains and the coastal areas of Victoria, to structural geology of some water storage projects. In the discussion on this paper, training of geophysicists and geologists was dealt with in detail.

Mr N.P. Merrick of the New South Wales Water Conservation and Irrigation Commission (WCIC) dealt in his paper with the resistivity depth-probing method. After introducing the development of the method and its theoretical basis, he concentrated on the pole-multipole electrode arrangements, the field operation, and the interpretation. This paper forms a major contribution on the use of this electrode arrangement which is used routinely in WCIC geophysical investigations.

D.L. Rowston, of the Geological Survey of Western Australia, described the results of an integrated geophysical survey for groundwater in the western part of the Canning Basin. Seismic refraction and resistivity methods were used, supported by drilling and logging operations. The maximum thickness of the sedimentary sequence was 590 m. Seismic refraction methods indicated the thickness of the sedimentary rocks within 10 percent of those proved by drilling, but the method failed to indicate any subdivision of the sedimentary sequence. The resistivity method did not produce good results when compared to drilling. As the results of this survey will be published as a report, only an abstract of the paper and a full discussion are given here.

B.E. Milton and R.G. Nelson of the South Australian Department of Mines in their paper on "Seismic investigation of hydrogeological problems" gave a concise and thorough account of the seimsic refraction and reflection methods, covering the use of both compressional and shear waves. The methods are well illustrated by several case examples from groundwater surveys in unconsolidated alluvial, sedimentary basin, and basement environments.

S. Handcock delivered a lecture prepared by Australian Groundwater Consultants Pty Ltd. The paper complemented the lectures of D.E. Leaman and D.T. Currey. It not only stressed the work of the consulting geophysicist in groundwater investigation but also gave detailed examples of the application of geophysical methods, their relation to other exploration tools, and the sequence of operation. This was illustrated by two field examples.

E.J. Polak and G.R. Pettifer of BMR, in their paper on "Current Practices in Groundwater Geophysics", summarised the main geophysical methods used in groundwater exploration in Australia. The principal groundwater regimes encountered in Australia were identified and the application of each method to each of these regimes was discussed on the basis of BMR experiences in groundwater exploration. In the oral presentation of the paper numerous examples and case histories from BMR surveys were presented to illustrate points raised in the paper. The reader is referred to BMR publications for a more complete presentation of these case histories than is permissible in a short paper.

The proceedings have been published in microfiche form because of the prohibitive cost of hard copy for such a large publication. Some of the illustrations to the papers were not intended for microfiching and if hard copy of papers or illustrations is required the reader is referred to the individual authors.

The editors accept ultimate responsibility for any editorial changes in this publication. We wish to acknowledge the generous assistance of many individuals within BMR in the editing process: H. Oldham, E.P. Shelley and D.C. Ramsay assisted with editing and proof reading of the manuscript, the staff of the BMR drawing office prepared illustrations for microfiching; and J. Kopras typed the manuscript. In addition, the individual authors edited the transcript of discussions on their own papers.

The editors and participants found the symposium to be a rewarding experience. The general consensus was the need for further symposia of this type and particularly the need for publication of more case histories on geophysics in groundwater exploration in Australia.

E.J. POLAK

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PHILOSOPHY OF APPLIED GEOPHYSICS

D.E. LEAMAN

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Introduction

Other papers at this seminar have considered user attitudes, consultancy, and details of the methods most commonly used in groundwater exploration. Many valid points have been made. However, unless all concerned with a geophysical operation are aware of the problems and limitations associated with the techniques, communication and credibility gaps may rapidly develop. The fault can derive from several quarters. My aim in this presentation is to sketch out the relation between the methods, problems, and desires, and so offer what I consider to be a workable philosophy comparable to that accepted in other fields.

Geophysics and its place?

This topic is basic to the philosophy of all applications and is the key to all gaps. There are so many misconceptions and misunderstandings in this area that it is surprising that the gaps are not wider.

Geophysics is generally defined as the application of physical principles to earth study. It is a broad term with wide ramification. Pure geophysics aims to deduce the physical properties of the earth from associated physical phenomena. Applied geophysics is generally concerned with the investigation of specific, relatively small near-surface features. Thus it is not a black art; but to those who see a black box, then a set of figures, and finally an interpretation, which may hopefully prove to be correct, it may seem so.

The methods of geophysics can be highly mathematical, but success rarely depends on more than directed arithmetic and a realistic approach. In any event mathematical usage should produce only a technical gap and never a credibility deficiency unless related to flaws in approach.

The claim of geological unreality or mathematical simplicity is often valid and by definition is a sign that the geophysical practitioner is ungeophysical (see next section). Interpretations that are more detailed (mathematically) than the data and request require are similarly ungeophysical.

Whether the query is posed by geologists or engineers then geophysics must be consistent with their needs since it is a tool science.

Geophysics as a geological tool?

It should be recognised that geophysics is but a means to an end and not an end in itself.

At this point two other hydrogeological and engineering tools should also be mentioned: the drill and the pump. No one proclaims a communication or credibility gap about either of these devices or the associated procedures, and yet geophysics is analogous. Apart from providing a hole the drill yields a sample which allows recognition of rock type but core or chips are only a fair gauge of quality, strength etc. Drilling is also a very expensive process which can be wasteful.

The pump likewise provides the only guaranteed assessment of the water-bearing properties. But there are problems - hole development variables, adequate assessment theory, etc.

Geophysics can never replace either the pump or the drill, and this should never be the aim. The techniques are complementary. Geophysics is more basic since it, along with other geological methods, can guide the use and placement of the far more expensive drill and pump. While these are ultimately essential there is little point wasting the former and no point experimenting unnecessarily with the latter. Yet some take a pride in wildcatting.....what is more expensive?

Geological methods include mapping, map and section synthesis, stratigraphic and structural techniques, petrological and petrographic methods. In brief - use of the pick and microscope. But such methods are essentially surficial and areal and lack a vertical component. Geophysical methods can assist by providing volume assessments which often contain much more information about the third dimension. Applied geophysics is thus a direct complement to the geology. The method summaries (below) indicate which uses and circumstances could provide various types of geological perspective. For example if one has both a magnetic and geological survey then not only are there two types of areal information but the magnetic map often reflects the subsurface features far better than the geological map (if only we can interpret it!).

Where the drill is expensive and limited in its sampling the geophysical methods need not be. Consequently direct comparisons on the overall rock state between geophysical results/ interpretation and core are often diverse. I would accept the drill results for primary lithologic changes, types of weathering products, fracture details etc., but the geophysics for a statement of whole rock conditions. Compatibility is not always a rarity.

All geophysical methods allow some bulk survey; the potential field methods (magnetic and gravity) most of all. In this way the methods support the geological section or map and with no more fundamental assumptions or errors than those contain. Simply, the data are physical and not obviously geological. The geological map is made up of direct observations and much interpretation (the amount depending on scale and time spent) and its section is pure interpretation (especially for shallow or small features). Similarly, the geophysical map is observed (if often inadequate and incomplete) and its section is also pure interpretation. In practice any method (provided it was chosen with due regard to rock characters) will provide some perspective to the geological map and section by reducing the number of geological possibilities. In addition information of hydrological interest will be obtained (geophysics and drilling share this advantage).

Geophysics as an engineering tool?

In the previous section it was shown that geophysical methods are valid geological tools - albeit secondary ones which can only be legitimately applied when something is known of the geology. The position in engineering investigations is not dissimilar, but in this case some idea of the geology and a series of questions come first. What information is needed? Rock state, joint frequency, trends, overburden, strength etc.?

Given the necessary constraints the methods can yield structural data and volume assessments of a rock mass. How are the geophysical results and interpretation to be related to the inevitable drill hole and lab test? As an example consider the use of a seismic refraction survey in the region of a fractured and weathered igneous rock. The velocity profile will yield some information about soil thickness, weathering thickness and state, and rock state.

The 'rock' velocity may be 4500 m/s. Now if experience with the particular rock type shows that velocities in excess of 6000 m/s represent massive rock, either unjointed or with tight joints, and velocities between 4000 and 5000 m/s represent slightly altered rock with a number of weathered joints, then a mental picture can form. However, a drill hole may encounter few joints due to its placement with respect to the fracture system and thus give a very different view. It is also only a point sample. Then if lab tests on the core are compared with the inferred overall elastic modulus implied from velocity information there is the inevitable disagreement. This need not be a cause for concern as one result represents a static limited load test and the other a bulk dynamic test. Both are unrealistic in different ways, but each does say something about the rock if we would have the patience to build a comprehensive rock-data-response file. All results should be treated with caution and used as guides. Personally I would accept the lower figure (normally the geophysical) and thus use a conservative factor of safety.

In many deeply weathered situations where kernelisation has occurred, sampling and testing may be very misleading if no allowance is made for other data. Again, the methods should be regarded as complementary and not contradictory.

The geophysicist?

A subsidiary question may be asked - how important is this person? In the broadest terms a geophysicist is one who uses geophysical methods, and thus his background may be very variable - in geology, physics, geophysics, engineering etc. This is true also of the so-called specialist geophysicists. The width in background need not be important providing he has a sound attitude and takes his user to heart. However, it should be obvious that where the geophysicist is dealing with a geologist of whatever shade he is going to be more sympathetic to the needs and problems of his 'client' if he himself has his geophysical 'know-how' superimposed on a geological rather than physical background. This is not to say that one background is necessarily better than another; rather it is a difference in approach. A willingness to benefit the 'client' (attitude) should balance the background differences since, for example, the geological background must be physically tempered if competence, confidence, and breadth of usage are to be attained. Considering all this one can see that the geophysicist is a technician only, a translator of the physical to geological or engineering requirements. In that sense he does not really exist, simply because the geophysicist should be a 'geologist' or 'engineer' when dealing with appropriate clients.

A corollary to this conclusion would be that any geologist or engineer desiring information which could be provided by use of geophysical methods should do the job himself. There can then be no basis for credibility or other gaps. Of course this is unreasonable for some or all in all cases, but not (in my view) for some or all in certain cases. The cases can be simpler applications and methods, and there is no better way of learning what is involved in the so-called black art of geophysics.

If the geophysicist is acting on behalf of another he must clearly establish the needs of his 'client', think long about the problem, and then select what appears to be the best approach. A pre-programmed standardised off-the-shelf approach is generally a poor one simply because so few have a good shelf. Jargon is unnecessary and only instrumental and descriptive terms have value.

In short, the 'geophysicist' is not a god but an aide, or technician. With these points in mind there should be no case to argue that "he ignored the geology....etc. etc".

The pertinent methods?

In groundwater exploration the geophysical methods fall into two categories: basic and 'exotic'. Two of the basic methods have been discussed previously in this seminar, but they are re-included here for completeness and because a summary of comparative strengths and weaknesses is given.

The basic methods:

Seismic refraction and electrical resistivity methods have long been the cornerstones of the geophysical family of methods in shallow groundwater and engineering applications. However, the magnetic and gravity methods can also be considered more basic than exotic in this context.

Refraction:

(1) Used for assessment of weathering state and thickness, overburden estimates, occasionally water-table depth, rock quality, joint directions. All uses are conditional on adequate geophone lay-outs and the presence of a velocity contrast.

(2) The method is normally simple to apply in the field, the data are easily reduced, and interpretative procedures are direct. The velocity values determined are always of some value even when a depth cannot be reliably ascribed.

(3) Doubts and problems arise when there are interface dips in excess of 15^{o}, steep junctions between units, curved velocity profiles. The method is restricted to line assessments and provides slow and expensive area coverage.

(4) Thought must always be given to geophone spacing, shot extension and depth as well as traverse placement and spacing.

Resistivity:

(1) Used for the assessment of weathering state, overburden, water depth, water quality, and joint directions. As a method it is more applicable to hydrological data measurement than the refraction technique which is more satisfactorily applied to structural problems - at least in new situations (see below). All uses are conditional on presence of a resistivity contrast.

(2) Field techniques are simple and, as indicated above, the method is readily water-oriented. It lends itself to easy traversing and simpler area coverage than does refraction.

(3) Qualitative interpretations can be very useful but require a large file of data before they can be applied. Quantitative interpretations can be complex and ultimately depend on proving and file reference also. All initial interpretations are more vague and ambiguous than refraction interpretations.

(4) Thought must be given to electrode spacings, topographic effects, and surface variations.

The two basic techniques sketched above can be combined to formman integrated approach for optimum resolution of results. Comparison of the results from the two approaches can permit differentiation of weathering from salinity problems, for example, and often confirm other indications. It is certainly not recommended that either method be used when starting a project in a 'new' area, although at a later stage when a collection of traverses, soundings, or interpretations are available direct qualitative and sometimes quantitative readings may be possible from one method. The reference file utilised in this way may need to be very localised to be useful if the rocks show regionally extreme variations in character.

Magnetics:

(1) Used for location of rock junctions, trends, and occasionally weathered areas and jointing. All uses are conditional on the presence of a resultant magnetic contrast whether due to susceptibility or remanence.
(2) The method is easy to apply, is cheap, and yields area coverage.
(3) The absence of magnetic materials may be limiting in certain conditions, and detailed interpretation, while usually unnecessary, can be difficult.
(4) Much thought must be given to the magnetic properties of the rocks to be considered, the station spacing, and the line density and orientation.

Cross-correlation of the results with other methods will provide more satisfactory conclusions.

Gravity:

(1) Perhaps too little used, it is a structural method with applications restricted to igneous features and overburden problems which must be significant. All uses are conditional on the presence of an adequate density contrast.
(2) The method is direct and yields wide coverage.
(3) A potentially awkward and expensive reduction is required.
(4) Thought must be given to station spacing, likely scale of the features examined, and topography.

Lest the reader of the above summary presume that the methods are inherently useful and reliable, and provide sound, unique interpretations it must be stated that this is rarely the case. Use of the methods must be conditioned by experience, pre-application evaluation, and the nature and properties of the rocks present. The last is the factor most often overlooked.

Any method may be used at the wrong time or in the wrong way in an assessment. Refraction methods often fall in this category. Quite often the wrong method will be used whether by necessity (the correct method being unavailable) or mistake (due to lack of rock data). Empirical experimentation is not included in this comment.

It should also be apparent that the use of any method, but especially electrical or seismic ones, prior to a statement of geological knowledge is a hazardous, wasteful, and foolish procedure. In some cases all four basic methods can be used together and then the information awaiting drill confirmation is minimised.

The other methods:

Several other methods normally considered (because of irrelevancy or expense) to be restricted to mineral exploration can have application in the field under discussion. Such methods include induced polarisation, electromagnetics, mise-a-la-masse, geothermal, and exotic applications of resistivity configuration. Some of these procedures are currently being developed for use in groundwater and engineering problems.

Induced polarisation:

(1) Used for differentiation of clays, weathering products, and saline waters. Generally used in unconsolidated material.

(2) The method should be associated with resistivity techniques and has comparable strengths, weaknesses, and planning needs.

Electromagnetics:

Very limited applications for joint, fault, and shear location. Generally used in hard-rock.

Mise-a-la-masse:

Limited application for tracing major joints, shears, and faults. Generally used in hard-rock.

Geothermal:

(1) Used for evaluation of thermal areas, thermal waters, flow regimes.
(2) The method is direct and can yield wide coverage.
(3) The problems of surface variability, sensor contact and depth, vegetation, and topography may be serious and interpretations - especially of attempts at flow regimes - may not be conclusive.
(4) Thought must be given to requirements, likely problems. The method is under development and the uses are likely to be largely restricted to unconsolidated aquifers and limestones.

Exotic resistivity:

Included here are the methods which use rotated arrangements or squares.
(1) Used for orientation, frequency and dip(?) of jointing and dip of bedding and major features such as shears or faults.
(2) All the strengths and weaknesses of standard resistivity methods are compounded and the techniques are under development.

In general the basic methods can often be profitably abused yet something of value can be salvaged with every use. This need not be the case with the 'exotic' other methods, which require more forethought, skill in use, and care in interpretation. However, on those occasions when they can be used - often critically - the use is very worthwhile since the more rock properties utilised, the more absolute the interpretation.

Strengths and weaknesses?

The strengths and weaknesses of the various methods have been summarised in the previous section.

The great strength of the methods as a group is that each yields a different perspective on the area studied and provides some information on the third spatial dimension. The prime weakness is that this information must be converted or interpreted into usable geological or engineering terms. However, this does not mean that the information is irrelevant, since it is a reflection of the rock characters present and is part of the whole picture.

An effective survey?

An effective survey may be regarded as one in which useful information is obtained with a minimum of fuss and to the satisfaction of the 'client'. A number of factors contribute to this state irrespective of whether the 'client' is also the 'doer'.

An effective survey is well begun. A geological background with rock assessment must be to hand before methods, or particular uses of methods, can be selected. The integration of methods, if possible, is advisable and potentially critical. The amount and detail of interpretation should be in proportion to the method and the controlling knowledge. Credibility loss often results from an overdone interpretation. With a first tier of information to hand some drilling at desired or critical points will enable tighter constraint and possibly more reasonable re-interpretation. More survey may be required. An effective survey is rarely an instant success, but the result of an iterative process with each stage used to compile a little more of the whole condition.

Formulation of philosophy:

The cornerstones of a workable practical philosophy have been laid in the foregoing outline.

A number of general factors may be stated and should be recognised by all:

(1) Methods of applied geophysics COMPLEMENT other approaches.

(2) The weighting of geological, geophysical, drilling, or other methods in any investigation will vary according to time, money available,

nature of problems etc., but in general no single category can ever be omitted or neglected without wastage, inefficiency, or inadequacy.

(3) All methods have a range of uses which are conditional on the problems, situation, and rock properties.

(4) All methods have drawbacks.

(5) Geophysical methods can provide vertical projections.

(6) Geological AND geophysical methods can guide the drill and optimise its value but never exclude it (valid vice-versa).

(7) Some surface geological methods and analysis (including geophysical) should precede the drill.

A further series of comments may be made with respect to the 'doer' or geophysicist.

(8) He must be well-informed on the geological conditions of the area.

(9) He should avoid unnecessary jargon.

(10) The methods to be used and the nature of the application must be carefully considered. If only a limited range of method integration is possible or used then the results will be poorer and should be so recognised.

(11) Interpretations should be compatible with available geological data and should lead to re-assessments and not absolute solutions early in a project. Advanced interpretations are rarely appropriate until the last stages.

(12) Iterate and integrate. Work on as much feedback to and from geological and drilling work as possible.

APPENDIX

The following quotations are typical of comments directed against geophysics and geophysicists. Each may have a limited range of validity, but all contain important implications which are cryptically noted.

The expressions are very common and represent various types of gap: credibility, ignorance, communication, information....or stupidity.

The word 'it' in the following could refer to geophysics in general or a method in particular and may need to be established. The words 'he', 'they', 'them', etc. refer to geophysicists.

1. "It is a black art..." Discussed in main body of paper. Betrays a misunderstanding of what geophysics is. Geophysics, like any other science or study, has an esoteric zone and does involve per-

sonal files of experience and intuition. It is no more an art than any other natural science.

2. "Too mathematical..." A common excuse for refusing to have dealings with the subject. Some techniques and practitioners are too mathematical, and perhaps they should be avoided or at least put in perspective. However, by its very nature geophysics must embody some arithmetic...whether in reduction of data, interpretation or modelling etc.

3. "Ungeological...unrealistic...simplistic" Often all too true. Occurs where a model is over-simplified, simplified for convenience, created without regard for other external geological data, or where too few property details are available. A geologically realistic model implies a lot of detail and control.

4. "He ignored the geology..." Sadly, too common and true. Simplicity and geological realism must occasionally be compromised to obtain limits or possibilities.

5. "Too expensive..." This may depend on the methods chosen and the application but must be put in perspective with other costs - such as drilling. How does the quantity and quality of information relate to money spent or funds available?

6. "I was confused by the terms he used..." Could be the result of ignorance on one part (forgivable) and lack of consideration on the other (unforgivable).

7. "I didn't understand what they were trying to do..." As above. Some idea of the capabilities of the techniques is always useful. One doesn't dig a hole in a wooden beam - a drill is used and tools cannot be ignored. Of course, 'they' may have been groping or operating without adequate forethought also.

8. "Too descriptive..." Usually results from a lack of useful interpretation but could result from a poor choice of methods and application.

9. "It's never accurate enough anyway..." Results from a misunderstanding of the methods, their limitations, and the function of geophysical applications. The drill cannot be replaced. This is a non-comment since approaches are complementary and not equivalent.

10. "In the end it didn't seem relevant..." Usually results from a poor choice of methods or poor interpretation.

11. "A waste of money..." There may be odd circumstances where this is true (compare 5). It is not a general truth and every case should be considered on its merits.
12. "He left us with rows of figures..." This is plain stupidity unless the client asks for it.
13. "We couldn't understand the results..." This will depend on the presentation and reason but usually it means a hopeless report. There is no excuse for it. "Results" here usually means conclusions and arguments leading to them, rather than the figures.
14. "The answers can be changed to fit the facts..." Often true. Note that interpretations may need to be iterative, and a first effort could be little more than a guess. Note the inherent ambiguity of many methods.
15. "You never get two of them to agree..." The reason appears in 14. Note that an interpretation is one man's opinion.
16. "We tried it but it didn't work..." What does this mean? A null result can be useful. Usually bad choice of method is the reason.
17. "It doesn't work in our conditions..." Could be true but could result from misapplication and is never true as a blanket statement for all methods.
18. "You've got to have a hole anyway..." True, but no excuse for no geophysics etc. Two things need to go together. The geophysics that is done should enable wastage to be minimised.
19. "A core! Now that's really worth something!..." Worth exactly what? See discussion in paper.
20. "A diviner is better value..." ?
21. "I prefer my hunches..." !?
22. "There's more to it than meets the eye..." True of almost anything but no reason to shy away.
23. "I would never use it!..." Never??!
24. "It ceases to surprise me that they are sometimes wrong and now amazes me that they are so often right!"

In conclusion, recognise that -

----geophysics is the in situ measurement of the physical properties of portions of the earth.

----the measurements may involve some minor assumptions but the values represent real characters of the materials tested.

----the measurements must be translated (interpreted) into familiar physical concepts which permit ready and practical assessment.

----the translation process involves judgment which is coloured by experience of what may be relevant.

----the measurements must be compatible with a self-consistent geological framework.

----as a story loses something in the telling, so do the physical measurements receive modification in the translation.

DISCUSSION on D.E. Leaman's paper

F. Eddington (Water Resources Branch, NT)

I would like to discuss Dr Leaman's paper in light of our reference; where we are supposed to be discussing the bridging of the credibility gap between hydrogeologists, geophysicists, and engineers. I think that Dr Leaman's paper is quite a contribution to this. What I feel he said in essence is that we are geologists, geophysicists, engineers, and other sundry workers, that we tend to regard ourselves as just these things alone, and I think this is really the problem. He has produced a rather neat little diagram where he indicates that a request finds itself a way, someway, into the geological and geophysical area; introduces itself into the system, and is converted to knowledge through choice of geophysical methods, interpretation, communication and back to where it started. This type of diagram to me is immediately reminiscent of the type of thing which management consultants dish up when they ask you to say how you are managing your operation and in fact this perhaps is where we are making the mistake. We are operating as individuals and very rarely do we appoint anybody or designate anybody to be a manager for a particular activity. How often does the groundwater investigation organisation, contractor, or consultant or what have you actually say "Here is Joe Blow and Joe Blow is the manager of this exercise. Now Joe Blow will investigate exactly what is the objective of this exercise, will design it and will lay it out precisely, check what knowledge we have, check what ways we have of acquiring extra knowledge, check the value of each of these ways and then proceed to co-ordinate, manage and direct this collection of extra information. Then finally feed all of this information into the appraisal and check this information as it comes out of the appraisal to ensure that it does match the requirements stated in the original objectives". Now this is a simple management cycle. I think it behoves us, and this is the point that I would like to make very clearly, to make sure that all of our various specialised investigation departments work together coherently in whatever organisation we belong to. I think if we can all accept that message then Dr Leaman deserves our debt of gratitude.

Mr Crawford (Darling Downs College of Advanced Education)

I think I'm the only Queensland voice here, which, it is fair to say, is typical of the general attitude towards geophysics as applied to groundwater in Queensland. I agree entirely with Dr Leaman's comment that the best way to bridge this communication gap is to make the user the consumer, and I can illustrate this very briefly from my own personal experience. After three years' experience of basic geology and a basic degree in geology I was appointed as a geologist to a geological survey in West Africa. The country was very poor in terms of resources and economics and I was given responsibility for a very large area of that country which had no geophysical services. I was responsible for normal mapping, groundwater engineering, and various other projects as required. Problems arose throughout the time that I was there and the solutions to these problems were almost inevitably partly or wholly geophysical. It was forced upon me whether I liked it or not to become a rough and ready bush geophysicist. I was also forced to construct my own geophysical equipment and therefore indirectly came to appreciate the value of well conducted, accurate geophysical surveys. Perhaps some of the comments that I am about to make are as a result of having to do it and learn it the hard way. In subsequent dealings with geophysical contractors I found one of the major problems is that the geologist can rarely identify what his problem is in the first place and can very rarely specify exactly what he is trying to solve. I think that's vital; secondly I think there are a lot of problems from the side of communications of the geophysicist, particularly in his report writing.

One we have touched on is the inherent ambiguity of geophysical methods. I think it should be made absolutely clear when writing a report that inherent ambiguities exist, that errors are possible in the interpretation and that instrument errors are possible. I think the geophysicist should also specify that there is a real need for independent control. He should specify that if there are more holes this interpretation can be very much improved and in this way the information from the hole can then be assimilated back into the geophysical data. I have read a lot of geophysical reports in which the common error is made in not separating observations from interpretation. It is vital to outline methods and observations quite independently from interpretation because once the two are confused you don't know what is observation, inference, qualitative or quantitative interpretation. This is generally a confusion which exists in the mind of the reader when he does not know the method too clearly. If the method is outlined clearly in the report, with references, he can go back, find out how the observations were carried out, and perhaps appreciate the inherent ambiguity more clearly. Finally there are the lateral effects, the off-end effects caused by variations away from the area of investigation. I think these should be clearly pointed out in the report. The geologist tends to accept the geophysical report at its face value, and if the report does not agree with his geological data he tends to dismiss it as being geologically unrealistic. Perhaps if the geophysicist would stress the limitations of these methods more clearly the user (geologist or engineer) might regard geophysics more sympathetically.

D.E. Leaman

I agree. I think we have already touched on this, we have to be honest. We have to record all the possible alternatives, we may not see all of them but I think it is important to record the ones that we can think of. I think this is part of the basic communication process whether it be in writing or orally. With respect to the specification of problems I agree that quite often you may not know what the problem is going to be, but normally you have some idea of where the exercise is going to lead. So you are going to request certain things and a lot of other things may be requested along the way which you obviously can't predict. Hopefully by the time you have finished you will have at least some limits on the problem; you often dig up the skeleton which wasn't expected anyway. This seems to happen on almost every survey. Something is uncovered which was not expected. I don't think it is wrong for a person to ask "what can you tell us about a particular area?", even if it is just to determine soil thickness. It may save a lot of auger holes, provided the auger holes are expensive and geophysical methods are cheaper.

W. Williamson (NSW Water Conservation and Irrigation Commission)

The discussion has touched on one of my pet themes of many years, that of report writing. I think it says something about the deficiencies of our university system that a student need not be required or qualified to write a report. In the last couple of years I have been appointed to a visiting committee in the School of Applied Geology, University of NSW and I raise this point of introducing report writing as part of the course. Going back even further I was rather aghast to find that one of our Universities in NSW, the Macquarie University has disposed of English as an entrance qualification to the university. I think this may reflect on the standard of report writing in the long run. It comes back to the problem of communication: if we cannot communicate what we mean honestly and factually then we have defeated ourselves in the exercise.

D.E. Leaman

I think a lot of our problem is that it is possible to get our message across when talking to a person face to face even though he may not understand some of the terms that you are using. It is still possible to talk away to him so that he eventually understands you. This problem is of course much harder to solve if we are just writing a report. We are brought up to believe that a report should be concise and also that it should be written in the third person. This I think is a lot of the problem. To write anything in this awkward, backward impersonal way is very difficult for anybody. I suggest that a little bit more of the first person, which is possibly heresy in scientific literature will solve a lot of the problems.

Mr Crawford (Darling Downs College of Advanced Education)

I have a lot of students who have come to me and said "Can I write a report in my own language?" I have accepted this and have found that they have put a lot more into it. They just do not know how to say or get sick of saying, "it was found that", or "on closer examination, this, that and the other", etc. They would much prefer the first person; it is not publishable but they produce a much better report.

F. Eddington (Water Resources Branch, NT)

Why is this not publishable? I feel this is just a prejudice.

Mr Crawford (Darling Downs CAE)

Because editorial boards would just not accept this sort of thing; there has been a big war in Geotimes that any report has to be in an acceptable academic style.

D.E. Leaman

I think in fact that this is the heresy. The first person, sensibly is a valid style.

Mr Crawford (Darling Downs CAE)

In terms of style, I think it is of vital importance that a geophysicist in expressing his data and interpretation should also present his physical model. I've seen many a report where this physical model is left out, and I have found that a geologist understands a physicial model better and can relate to the interpretation. So that, for example, if you are approximating your actual geological case to a sphere, sometimes the actual relation between your actual geological case and the sphere or your approximation is not stated. Often this leads to confusion; the geologist may even think that the actual geological case revealed by the geophysics is the simple approximation adopted.

F. Eddington (Water Resources Branch, NT)

I think I've already discussed this point. They know this. We are expressing an opinion often subjectively, and the best way to state an opinion is "That's the way I feel". I would much rather have somebody report to me in this manner rather than say "It is felt that", or "it is considered that", etc.

E.G. Wilson (BMR)

I would like to discuss the boring subject of reports by engineers before they send the reports out as part of a tender document. Now, your geologist's report gets divided into one area of fact and the other area where he has put his conclusion, and what the geological facts mean in his assessment of these. Often this assessment gets wiped right out. And this is often the case with the geophysicist's report. Often the field data go into the contract document with perhaps interpreted cross-sections, and this is perhaps all. Often the geophysicist's report goes via a geologist to the engineer and is generally appended only with the geological report. I would be interested to know how many people here have produced a joint geological and geophysical report for anybody at all. These are just aspects which bedevil tender documents at the moment, but I believe the time is coming when the assessment of the geologist and geophysicist will also be included with the basic data in tender documents, with the qualifications clearly spelt out for the tenderer or contractor.

J. Odins, (NSW Water Conservation and Irrigation Commission)

What the previous speaker said was perfectly true. I am one person who has written a joint geological and geophysical report - but only one, which I think to a certain extent proves your point. Co-operation in a joint report is one of the easiest ways to close the credibility and communication gap; by actually talking somebody into joint authorship of a report, we are starting to win the battle. This led me to consider the honesty of one's approach, and I could perhaps summarise with some 8 points. Credibility, which I take to mean trust, is based on experience. The work load must be split in a joint report and therefore we must consider the following questions:

(1) Exactly what do we want the geophysicist to do?

(2) Is the geophysical group that you have selected competent to do the job? I think this is extremely important.

(3) Is exploration geophysics applicable to the problem, and we are now getting deeper into the problem.

(4) Are the selected geophysical methods applicable?

(5) Are the limitations of the methods understood?

(6) Is the supplementary information obtainable from geophysics and geophysical surveys likely to be useful?

(7) Is proper control available at the start of the survey and during the survey for proper evaluation of the efficacy of the techniques proposed?

(8) In consideration of the previous 7 points is the application of geophysical methods economical? Now I suspect in a lot of cases one assumes that the methods are applicable, one assumes that the people are competent, one assumes that what these people intend to do is relevant to the survey. I believe that some of the failures of geophysics are due to the fact that some of these assumptions are wrong.

D.E. Leaman

I would agree with that and I think number 7 which dealt with the degree or adequacy of control of the geophysics is a key. I think we can perhaps expand this, and if we have an organisation with strict categorisation of disciplines, then we should ask, has somebody from the other category had a look at a similar problem? I know that mining companies are a much greater example of bad practice in that they use geophysics as a means of getting their first step in their file of information, which is bad news. For example it is very common practice to use aeromagnetics over large areas which nobody has ever really looked at. The principle of this is inherently bad. What is needed is someone to be there to examine the rocks to determine what their relationships are, and unless the whole thing is covered with soil or alluvium of very great thickness then this practice must be inherently bad.

I think this was bound up in what you are saying but I would agree; if we have to categorise people then the geologist is a person who examines the physical range of properties of a rock and the judgement that he would have to make, which is a physical judgement, will affect some of the other points that you made there. I have listed this point in my paper under physical concepts. For example, if somebody describes to you a granite then for right or wrong immediately you have in your mind a conception of what he is talking about and this conception depends on your background, and this conception of a granite may not be the universally accepted one, shall we say for example, in the American Geological Institute Standards. You have this conception of a granite and this conception may give you a feeling for some of the properties of this rock which you may call granite. If what you are calling granite is not what the other chap is calling granite then you have trouble. This happens, for example, where people may confuse igneous rocks of different properties in some way, but physically their properties may be the same. For example if we take Tasmanian dolerite and granite, in many respects, these two have the same physical properties but nobody who is a geologist would confuse the two. I think we have to be careful, terms can be hazardous. We do have to watch our terminology and terminology can go right back to something as familiar as that. So I think that the description that one offers from one person to another must be a careful description. For example, if I were to describe a rock of virtually infinite resistivity, compressional wave velocity of 6000 metres per second, density of 2.7 grams per cubic centimetre etc., one could immediately form a conception of that type of material but it could represent six different types of rocks. However, if somebody says to you, this rock is grey and has bedding then we can exclude half a dozen possibilities immediately. So once again I stress that the geological input is vital and can restrict the number of possibilities right from the very start.

Mr Crawford, (Darling Downs CAE)

With respect to the problem of communication gap between geologists and geophysicists I think geophysicists tend not to do the type of thing that a lot of geochemists are now doing, and that is, going into an area and scratching over it in detail. This is known as an orientation survey; I think users of geophysics are in the same category here. Also I feel there often is not enough experimentation with geophysical techniques, and often people do not go to engineers saying that if we spent 20% of our costs on experimenting with the techniques we would get much better results.

D.E. Leaman

I think the engineers will bear me out on this point; one finds that usually there is X dollars devoted to the thing called foundation investigation, or basic exploration. Usually this exploration has a time limit on it and that number X very rarely grows, in fact more often shrinks. These are very great constraints and without a lot of preparation for what is involved, which I think is part of the problem, it may require some experimentation. I know that for many years the Bureau has spent considerable time sorting out what type of methods will give certain information. This can be easily done perhaps by a government organisation where the costs or charges are not perhaps all that obvious. For example, in our own department in Tasmania, we will often do cost estimates for our own information and we often find that most of the money spent on the project goes into the drill and perhaps a minor cost for consumable items such as explosives, cables etc. Often these costs are lost because we are doing it for some other department or government instrumentality. We are usually only charging them for expenses. We do not take into account labour costs. If for example we did, and decided to sit for a week and experiment, then the cost of this survey or type of survey would be frightening. There is a tendency not to experiment and I think this is bad. There have been instances where survey exploration programs have been terminated or crimped due to time or cost factors, and very often design programs will go ahead with terminated or incomplete information. It requires an awareness that sometimes 10 000 dollars spent early in the exploration program may save a million dollars later on. The Bell Bay Railway in Tasmania is an example of this type of thing where the exploration was terminated, under great resistance. The judgement to be made is, what is more important, time or money, and at what stage? However, in the case of the Bell Bay Railway where the alignment was pursued, the engineers were not familiar with the geological realities. If anyone here is familiar with the properties of Tasmanian dolerite one does not put a cutting up to 30 m deep in Tasmanian dolerites which have a velocity of between 4500 and 7000 metres per second, or one does it and accepts the expense. In this case the exploration budget was crimped. Unfortunately also it is typical of a lot of the early stages of exploration. I think the whole process is very narrow. One has to get over the communication gap and unfortunately you are dealing with two groups of people who just happen to meet at the airport before the job; hardly conducive to getting good results, and these two groups only nominally understood each other's viewpoints. I can list at least 20 projects in Tasmania where costs have escalated due to inflation, and particularly because the investigations in the initial stages have not been sufficient. Take for example the Derwent River, where people have worried that they did not know enough about the river but bridges are still being built there and political and economic considerations over-ride geological considerations. Another error that is commonly made is when we often say to an engineer "Look, you can't build this there". They in fact <u>can</u>

build something there and have the power and position to do it. It may not be the simplest and cheapest solution but you can design anything you want, on anything you want, to do the job you want, on any particular site without any initial investigation. You can build your bridge or your tunnel and you make running corrections as you go. This is what I would call the old method of building things. It is a great blow to realise that what you are worrying about is in fact to the other person an intangible thing; to you, your experience of what the geological structures are like is colouring you - you are worrying about what the problems might be and you can forsee that if they don't drill this particular hole or look at this particular structure there will be problems. Thus persuading the other person that your worry may affect them is still the gulf that exists, and this is often because people live in different camps. Quite often you can write a geological report which is geologically sound, geophysically discursive in terms of the fact that all your problems are outlined, all the worries that you express are on paper. We are trying to get a practice where this is always done but still we find that these worries are swept aside. People say, well don't worry, we can get around these problems, and of course they do, but quite often if they had taken your advice they could have saved themselves a lot of money. However, this seems to be a fact of life. You can only attempt with time, if you have a message, to be honest and hope that you convince the person in your organisation or for whom you are working. We must realise that unless we can convince them we ourselves have failed. No matter how good our job is, unless you get your message across you've missed. For their part, they must realise that we may be able to tell them something. It is a process of attrition where both are being rounded; it's a very practical problem and quite often a political problem as well, and knocking down the political question is the real problem.

Mr Crawford (Darling Downs CAE)

If I may cite an example of this, something that is happening in Queensland right now, a drill rig became available uncommitted from an alluvial drilling situation and was transferred to Toowoomba, a basaltic upland situation with some 500 square miles of basalt, which has really serious groundwater problems. Thirty holes were allocated to be drilled in that 500 sq. miles, to begin to solve the problem, and the geologist in charge of the operation was informed about one week before the drill arrived. The Head Office, which was engineer-dominated, of course had no feeling for geophysics, and felt that the geologist should have been able to use those 30 holes to the optimum and get a lot of information out of it. Now perhaps, if 20% of the cost of those holes had been expended previously in some sort of geophysical survey then the use of these holes could have been optimised: part of the problem could have been solved in one program, and the other part in subsequent years. Using this approach to exploration, if nothing is done about it, we are going to gradually fill the Darling Downs full of holes over a number of years, which is virtually a tight drilling grid situation until eventually the opeople know what is going on but by which time there will probably be no water left in the ground because of the number of holes. This is the gap which exists because geophysics was not even given any recognition and nobody even thought of doing geophysics before the drilling. The geologist was given one week notice, as I have said, the engineer arrived and decided the best place to put these holes was in the creek, anyway, because that was where the most water would probably be. That wasn't going any way towards solving the groundwater problem at all. Now this is a credibility gap to the extent of a complete exclusion of the people who could provide a very excellent service.

F. Eddington (Water Resources Branch, NT)

Mr Chairman, it seems we are coming back to this management problem again. Somewhere along the line we are talking about 'them' or 'they', and head office being engineer dominated; it seems that we all assume that the engineer is going to be the man who is to carry out these managerial problems and without deserting my discipline I feel I should make it quite clear now that very few engineers have managerial qualifications or ability. Now if we are depending on engineers to organise these programs this is probably where these programs are going wrong. We need more people capable of handling these managerial positions and looking at what information is available, where it is going to come from, bearing in mind all the time, a precise, clear, and well communicated idea of what the objectives are, so that everybody in the organisation - be they geologists, geophysicists, or engineers or whatever - knows exactly what it is that they are aiming at, so that they all have exactly the same picture. It is no good me stating what I feel are the objectives unless anybody else gets the same mental picture of what the objectives are as I state them. If it is my job to formulate the objectives then it is also my job, I feel, to communicate and see that the message is communicated properly about the objective. It appears that the message is not getting through in many cases to many people at all, and I suspect in most cases that it is not even being formulated properly. If we formulated the objectives in a proper, logical fashion we would find that each one of the geophysical methods we have been discussing would be examined, its costs would be examined, and the benefit that is derived from using each of these methods would be examined; not on an impartial subjective basis by the man who happens to sit at the head of the organisation but on the basis of submissions made by people who know what these various techniques can contribute. If they also include with their submission an estimate of the cost of the particular method then the engineer or manager must evaluate in terms of the contribution the value obtained for the given cost of that contribution.

If he has X million dollars allocated for a project then it is up to him to see that the X million is allocated in such a way as to get the most value from the money spent and complete the project in the minimum cost and the minimum time. I've just mentioned time - time is readily convertible to dollars, and must be so, if we are to make a proper cost/benefit analysis, and it is only by doing such a cost/benefit analysis we can determine whether anything is worth doing at all. Obviously there are, as people have suggested, better ways of doing things. Maybe, for instance, it is not best to run a gravity traverse first off; perhaps it is better to send a geologist out there to collect rocks. This is probably the cheapest method also, and probably most productive of information, particularly if he has a good background map to work from. All this comes back to what I have been saying. We need somebody with reasonable skill to apply the managerial skills available today.

E.G. Wilson, BMR

Everything the previous speaker said is true, but one problem is the initiation. The initiation must come from the organisation which has the money, and only they know what they want to do, and until they ask "Well I'd better ask for some geological and geophysical advice in planning this program" the whole thing will fall flat. In engineering projects in Canberra we can work with the Department of Housing and Construction and they say to us "We would like to build a tunnel," and they ask for a geologist to work with them;

all we do is assign a geologist to their design team and he works with the engineers and, rather than writing a report - which he has to do anyway - he is engaged in discussions of actual design alternatives. As his investigation proceeds along the tunnel line he will remain a part of this team, and during construction as well, and he sees whether his predictions of geology discovered during excavation are correct as well. But he can only operate when he is called in: it's the man with the money who initiates the problem. The man who initiates must be both a good manager and a good technician to know whom he can best call on to get good advice.

D.E. Leaman

This is certainly a vexed question. When a problem does arise the manager or engineer, depending on what has been his experience in the past and whether he has worked with a geologist or whether he has done a course in geology for engineers, will determine whether or not he contacts a geologist. The engineer very often does hold the purse strings, and very often also the only communication between the engineer and the geologist is the report that the geologist produces. It is hard to break down, because a lot of organisations respect their own integrity. This comes back to the problem of the education of all concerned and that there are other people more expert in a particular aspect than they themselves and they should be able to recognise what some of the problems may be. Now in the diagram in my paper where I introduced a request into the system, I really did mean request. There have been many instances when somebody has come along to a geologist and said, what can you tell me about this area? He is being vague. And the answer that he has often ended up with is the detailed stratigraphy, and of course if anything is geared to turn someone off, then that is it. People in the earth sciences have often been educated to recognise every second fossil and that is it. They have never ever realised or thought about the fact that a client may not want to know that. Other people may go around spending their time measuring joints, which may be useful; but it is a vexed question and it requires direction from the management side as to what information is required, or involved in the project. We need heads together. One could say, this is the sort of information we have about the area you are interested in, we would need to look into this, this, and this etc. The second person would say, we can tell you more about that, if that's the case, but we shall wait until you've had a second look and we shall discuss it again. The other party, if there are three would perhaps say, this is what we're thinking of doing and this is what we need to know. It is particularly good if we can get one of your organisation onto the staff of the other organisation. This makes for instantaneous feedback. If there isn't this contact then often work is delayed and desk type geology is carried out. Again I stress that overall management is needed and this is what I meant when I said, in my formal paper, an "effective survey", and the word "survey" can here be taken in the broadest context. The request may be assessed for this single hectare, for example, to be used as a tunnel portal or a bridge pier as the case may be, and that implies that certain things are required from each party involved. If, for example, a bridge pier is to be constructed then the person concerned in the design has probably already looked up and down the valley to determine the best alignment for the bridge. The criterion which determines the placement of a pier is probably based on a population study and economic considerations or whatever, and geology is probably somewhere down the line. The request is generally of the form "we're putting piers in here, what's the foundation like?" You may then have to enlarge upon the problems as you see them, and then of course, depending on your answer, the requests may change. This may then require a decision to go to site B, but that is a judgement which a geologist can not make, and a geophysicist cannot make, and this is why I've used the term <u>tool science</u>. Knowledge is provided which enables somebody else to make a judgement and that somebody else will hold the purse strings. In essence it involves various shades of judgement down the line.

<u>W. Williamson (NSW Water Conservation and Irrigation Commission)</u>

We are dealing with the two words: management and communication. On the subject of management, as Frank Eddington has said, there are management procedures known, but how many of us are trained in them? Again this gets back to basic education. There are many organisations which provide basic training in management, but few people have taken advantage of these courses. Those people inevitably move from field positions where they may be technically competent into administrative or managerial positions. It does not necessarily follow that they will become good managers.

E.J. Polak (BMR)

I would like to cover a few points mentioned here. We wrongly assume that our work is divided into two disciplines: geology and geophysics. We are also presuming that geophysicists come purely from a scientific background. When I came to this country, in the Engineering Geophysics Group of the BMR (dealing with hydrology also) there were three engineers and two scientists. At present there is only one engineer. The problem is lower salaries for scientists than for engineers. The separation exists all the time between the groups. I wanted to become a member of the Australian Institute of Physics. I was refused because my degree is engineering. Similarly a scientist is not allowed to be a member of the Institution of Engineers, of which I am a member.

The separation starts from the beginning of training. Last year I visited the Institute of Geophysics in Poland. They closed all the geophysical training facilities in different universities and sent all the staff and students to the Mining School attached to the Cracow University. Six professors of geophysics were appointed, and a student quota system was imposed, including 25 PhD students per year. Training for the first two years is the same for geophysicists, mining engineers, and geologists. Later the students branch into six streams of geophysics. They have good laboratories and good equipment and the same standard of training for all. It shows already that centralisation in this case is paying dividends.

In his work the geophysicist often requires considerable knowledge and strength to challenge the observations and preliminary information he gets in advance of his survey. I know of an example of a private geophysical contractor who was given the level of clay (top of the bedrock) in two bores. A seismic traverse connected both bores, but the geophysicist was unable to fit his data to suit the borehole evidence. In the end, on the advice of the geophysicist, one borehole was deepened and passed through clay into alluvium.

The term "Black Box" of some magic as applied to geophysics is another interesting point. The Anchor Dam in the USA has never filled with water in its 18 years of existence. When water reaches some level, its pressure collapses a cavity in the limestone beneath the reservoir and the water leaks away. Several geophysical methods were used and lately a black box was brought in. The contractor refused to divulge the secret of the instrument. He discovered some cavities, but missed several others. We expect this was some kind of high-frequency electromagnetic method.

Dr Leaman

I was referring to Black Box geophysics in a less mystical sense and I would agree whole-heartedly with the point about conviction. However, it comes back to this problem of management. I think we have all been in the position where there has been a disagreement between the drilling results and geophysical results. We may not always understand why this is, but it is up to the person managing the project to offer suggestions why this should be. In my own personal experience I have been in the circumstances quite often where a driller has stopped drilling because he decided drilling was getting hard or he thought he was on bedrock. Later on people have come along and found that what he actually struck was a lateritic band. There was recently a case where a hole was out by 50 metres in 100 metres as predicted by the geophysical results. The hole went the necessary 20 metres and then struck granite. There was some initial embarrassment and a lot of argument about whether to continue the hole or not, particularly as our previous results in the area had proved to be quite accurate. The granite struck was a floater three metres thick. The material below was decomposed granite of the same velocity as the sediment above and the actual solid granite was at the depth that we had predicted from the seismic results. This residual proved to be important in the particular area and further follow-up work was done. However, in this particular case, the seismic was looking at one thing, the drilling at another and I feel that one would have had to stick to his guns in this particular case, believing the seismic results to be correct.

R. Gerdes (SA Department of Mines)

I have four points which I think are of great importance. One is information. There appears to be a lack of a lot of information that you can get as the geophysicist or geologist when working in a particular area. You may have a geological map but lack the immediate access to information on other work which is done in the same area. A lot of time must be spent on gathering this information. Files of information on a particular area should also relate to work carried out in similar areas. For example, in the Adelaidean areas, quite a considerable amount of work and data has been gathered and is available which would help, for instance, in a dam site investigation. You mentioned, for instance, orientation. If you had a drill hole in a lot of areas you could measure properties in the hole and solve a lot of your geophysical abnormalities. There is also the problem of feedback. Generally there is negative feedback: you only get feedback when there is a problem; when the results are good you don't hear about it. I can state an example from the freeway here where seismic spreads were carried out. In one place a spread was along the alignment of the road, in fact along a quartz reef. This might have been overcome by putting in a cross-spread as well; this was an error on the part of the geophysicist.

In problems of rippability of calcrete also a lot of problems could be solved by gathering basic physical data on the properties of calcrete. There also appears to be a great lack of published, well documented, case histories.

D.E. Leaman

I think this is true. We have to have a ballpark idea of the range of properties of materials. One has to be very careful because properties can change very quickly. This can be a source of problems when you are fresh into an area. For example, in northeastern Tasmania where we have Tertiary sands overlying weathered granite and fresh granite. We went into the area with a preconceived idea of the properties of these materials, particularly the Tertiary materials. Everywhere else in Tasmania the Tertiary is mainly clays with saline waters etc., and of course this colours you. People were prepared for local variations but we must still have an idea of the range of properties. I agree also that there is a great lack of case histories since these tend to get dispersed. The results as they are gathered are dispersed throughout the report. It is very rare to see a second report related to the first report published, which shows the drilling result and compares it with the initial results showing an evolution in the gathering of information process. It is unfortunate that it is not common practice to publish this type of thing because people coming new into the country or State are not familiar with the problems and what has been tried. At the moment I think we all carry around with us what amounts to local knowledge of techniques and applications and results. This ragbag is called experience. It's a pity this is not available for other people: if you happen to retire, die, or whatever, so much knowledge goes with you. This is a great loss.

Mr Crawford (Darling Downs CAE)

I think that this is ultimately something which could become the problem of a Mines Department. This may come about by legislation. Information is stored on the basis of map sheet area etc. The legislation could specify that any geophysical work done would have to be deposited in the form of a summary or report with the Mines Department as was supposed to have been done with mineral exploration, but unfortunately this did not work too well in Queensland. There could be a problem in policing this.

D.E. Leaman

This typifies the problem. Our department has a great stack of information on mining geophysics which is largely worthless, but even with that which isn't, the process of trying to sort out what fits with what, and what they did and what the total information is worth, is a very long-term project. It is a very difficult business, having the information on hand and trying to extract what is useful from it. It is a pity that there are not more seminars like this where the case histories are the main topic. This sort of thing would have to be organised probably on a State basis. There is a lot of information which is carried around and never put on paper. What tends to be written down is what is made to be written down and not what should be written down, because most people dislike the pen. Even recording a range of properties that were measured, just so that the file information can grow, very rarely happens.

J. Odins, (NSW Water Conservation and Irrigation Commission)

I would like to ask the question, what is going to happen to the results of this seminar. I think, at least I got the impression that most people are agreed about what the problems are; feedback and information is one of the problems and in this light, how can we propagate the discussion of this seminar outside to people who did not attend? I am starting to get worried that so far nothing really concrete has been proposed to solve the problems outside this group. I was thinking about a book which could be published evaluating the various methods in different conditions to be used as a basic reference for people using the methods. Dr Polak in his paper has done quite a lot of this already. I think that from the volume of material collected, there is almost enough for part of a University course. The course could perhaps include managerial courses for earth scientists, and I would like to ask people in the Universities or people with contacts in the University whether this type of course is at all practicable.

W. Williamson (NSW Water Conservation and Irrigation Commission)

The TCUW had in mind, that given a sufficient input in terms of papers and discussions the results of this seminar be published and distributed to appropriate water authorities.

Concluding remarks by W. Williamson

I think that Dr Leaman has made an outstanding contribution to the seminar, he has been largely descriptive, used very little mathematics, but has said things which I feel should have been said.

GEOPHYSICS AND THE CUSTOMER

D.T. CURREY

State Rivers and Water Supply Commission of Victoria

INTRODUCTION

The Bureau of Mineral Resources introduced geophysical investigation methods to the State Rivers & Water Supply Commission during the Buffalo River Valley dam site reconnaissance. The methods included seismic refraction, resistivity, magnetometer, gravity, and self-potential. The surveys were aided by boring so that a baseline could be produced for comparison with the geophysical survey results. The aim of the Bureau in demonstrating these methods was to enable the selection of the correct system for the changing conditions and also to enable the Commission to assess the expertise of consultants selected to carry out site investigations.

ATTITUDES

The geophysicists were particular in promoting an awareness that it was essential to choose the correct method for any particular survey. It has to be recognised that the engineer who holds the purse strings is often disappointed in geophysical results when the incorrect methods are used. This unfortunately has a long-term effect and would cause an engineer to look askance at geophysical methods, maybe for the rest of his career or at least for a long time.

Engineers are often disappointed with geophysical results due to a lack of their understanding of geophysics. The geologist is surprised when the subsurface boundaries calculated from the geophysicist's work do not coincide with his bore data. Also the geophysicist is disappointed when the engineer and the geologist do not use his work and calculations correctly. I wish to point out some of the reasons for this lack of understanding in each other's discipline. The technical expert requested to produce basic information for a project should understand the project well enough to recommend the type of survey needed. As an example, an engineer will regard say a particular gravel as a suitable foundation for a structure, and other gravel beds in the area as unsuitable, all being tested by him beforehand for their strengths as foundations. The geologist may recognise that the gravel beds are in different formations and may be of very distinct ages; in one case one gravel may be up to 4000 years old and another may be 20 million years old. A geophysicist will record the velocities of the gravel beds and the velocities may be the same, also the velocities may be similar to decomposed bedrock if saturated with water. The velocity lines could be connected across the gravel and the decomposed bedrock boundary. Excavations will expose these two different types of materials and the engineer may claim that an error has been made by the geophysicist. This is due to the lack of understanding of velocities by the engineer. The decomposed bedrock may be inadequate as a foundation material for the engineer's purposes, and here it is shown in the velocity section as being the same as the useful gravel foundation. Similarly the geologist would question the boundary shown on a geophysics map as intersecting his two distinct geological ages because of a similar misunderstanding.

This can be cited as a fairly simple example but in reality it is the type of argument which raises itself time and again during assessment of geophysical work for engineering projects. It has become obvious for these reasons that any one of the three experts should seek advice from the other, before and during the investigation phase.

Some examples of groundwater investigations will be given, followed by examples of the use by the Commission of geophysical surveys for dam site investigations.

GROUNDWATER

Groundwater examples will include investigations of riverine plains or very flat broad plains and the materials below them, the alluvium in the valleys, and the rock on the valley sides. These are three distinct settings and of course three distinct ages. Also the type of geophysical surveys which have been applied to the salinity problems and Koo-wee-rup Basin groundwater will be mentioned.

Riverine Plains Investigations

(i) Resources

The riverine plains are usually very extensive and gently sloping and have been built up over millions of years, and often comprise up to 200 m or more of materials deposited by rivers. Deposition is on one land surface after another as each is buried. It would not be unusual for some of the buried landforms to be similar to those of the present plain. There would be rivers, swamps, dunes, and a variety of similar landforms in the succession of buried land surfaces. Water from rainfall and river losses across the plain will percolate downwards until an impermeable barrier prevents it from penetrating any deeper. There will be numerous bodies of groundwater concentrated in sandy deposits below the surface, because of the percolation.

(ii) Problems

The groundwater problem in northern Victoria is due to irrigation water, which causes the groundwater to rise towards the surface. The groundwater is displaced towards the surface because the irrigation water is an addition to the annual rainfall. The groundwater table rises approximately half a metre per year in some areas, and will eventually affect the root zone of the various crops, and reduce productivity. Capillary action can draw the water to the surface, and when the water evaporates, a salt accumulation can remain on the surface and cause severe damage to all crops. This problem has caused great concern all over the world and to relieve it by drawing the groundwater down below the root zone, it is necessary to drain some of the water away. This is done either by open drains in sandy soils or by locating sand beds below clay soils and pumping from these sand beds. Sand beds occur along former creeks or rivers, which can be identified on aerial photographs although they may be from 40 000 years to 12 000 years old. There are other subsurface sand beds between these old drainage systems, but they have no surface expression and therefore cannot be located by aerial photography, but would show up on resistivity records. Resistivity surveys in the riverine type province have proven successful. In Gippsland an extensive resistivity survey was undertaken to locate sand beds, particularly along the old drainage courses, so that vertical pump drainage could be used to draw down the watertable. Pumps installed as permanent fixtures have overcome the groundwater problem.

Similar methods have proven successful in some areas of the Northern Plains, but the investigation is yet to be completed. Sections are being drilled across the Northern Plains particularly where the target areas have been selected along the old abandoned stream courses.

There is a variety of salinities in the groundwater on the plains, from 100 to 60 000 milligrams per litre total dissolved solids. Therefore resistivity methods may have to be restricted to the lower-salinity areas. The salty areas around Kerang proved difficult to survey with resistivity. Recently Eddie Polak, BMR, said that improved methods had been devised from studies at Lake George near Canberra which may overcome the problem.

There are bores being drilled in the various irrigation areas to locate aquifers so that vertical drainage by pumping can be undertaken. Geophysical methods in these areas have been successfully used over the years to locate sand beds under the plains. No doubt future use of the various methods will prove as successful.

The Mines Department and BMR are carrying out joint geophysical surveys to explore the deeper groundwater resources below the irrigation areas in northern Victoria.

(iii) Rivers and Lakes

Echo soundings have been used to study lake floor sediments. A number of lake floors as well as an old river valley were delineated below Lake Corangamite on the records of an echo sounding survey. Lakes Bullenmerri and Gnotuk, up to 80 m deep, were contoured by echo soundings. Work was also carried out near Lake Victoria adjacent to the River Murray and at Chowilla to locate the various holes in the bed of the river where saline groundwater could enter the river. Large irrigation channels were sounded to identify seepage areas and former stream courses, but these surveys were unsuccessful. Similar surveys along the River Murray did not indicate sediments below the river bed. Of course sparker systems should be used to locate this type of sequence below river beds. The echo-sounding surveys were used to plot the river bed, and the additional information was regarded as a side benefit.

(iv) Koo-wee-rup Basin

The Koo-wee-rup Basin is a wide sediment-filled basin bounded by Westernport Bay to the south. There are 70 m of sediments above lava flows with more sediments below. Aquifers occur in the sediments above and below the lava flows, and there is a suspected slow seepage through the lava. There are two large cones of depression formed each year by the pumping withdrawals. The bases of the depressions are below sea level so that there is concern that sea water encroachment will occur due to overpumping. The lower aquifers may be able to be connected to the upper by bores through the lava, but at the moment little has been done to devise methods for this connection. Pumping for irrigation water has been restricted to the upper aquifers because costs are too high to tap the deeper aquifers, perhaps 200 metres below natural surface.

The edge of the lava layer has had to be determined to assess the configuration and the volume of the water resource. This has been accomplished by geophysical surveys carried out by the Mines Department. Also some resistivity work has been used to determine the sea water encroachment. However, it has been difficult to determine from the results whether the sea water is encroaching into or towards the developed area.

(v) Bedrock

Water will penetrate and accumulate in fractured or porous rock. Also if there are faults disrupting the rock mass, water will penetrate along the fault line. When the rock is crushed along the fault line and a clay layer develops, the fault could pond up water behind it and form a groundwater resource in the rock. As there is usually a Mines Department in each State, or a Bureau of Mineral Resources representative close at hand, it is not difficult for the geophysicists to obtain geological data of any area. The sections and geological maps will certainly aid in his planning of a geophysical survey for groundwater, and discussions with geologists will aid in his initial study.

In other hard rock areas, such as in granite, groundwater will accumulate in areas which have numerous joints or shearing. The groundwater at the Honeysuckle Creek Station near Canberra, was found by a combination of geophysical methods and geology, by locating the intersection of the major shears and joints in the rock. The sheared zones showed up during a refraction survey because there areas are broken and contain water and therefore have a different velocity from the sound rock.

ENGINEERING PROJECTS

Tunnel

Another problem arises in estimating groundwater resources or rock quality below basalt. A tunnel was driven at Merrimut to connect two river catchments. A lava flow provided the divide between the two catchments, and below the basalt was a buried river valley. The rock conditions along the tunnel needed to be assessed for tunnelling purposes. However difficulties arose in using geophysics because of the high-velocity rock above the gravels. There are sediments below the gravels of Palaeozoic age and the condition of these rocks needed to be known to estimate the support requirements along the tunnel.

Cut

Groundwater in the granite at Khancoban, Murray 1 cut, caused landslip problems. The granite had been intruded by dykes, which decomposed to clay and formed impermeable barriers to water. These barriers pond the groundwater between them. The weight of the water behind the cut caused very bad slumping during excavation of 70 m cuts in this area. It was necessary to insert horizontal drains and drain the water out to overcome the slumping. If this sort of information is not known before an excavation starts, there will be a holdup in the operation. Resistivity and refraction methods used in such areas will detect and delineate the subsurfaces changes. The changes can be readily shown up because very high velocities, 20 000 feet per second, should be expected in fresh granite but in weathered material with water there will be a much lower velocity say 8000 feet per second. Of course, drilling can be used to delineate these zones but usually it is not known where to drill until the geophysical survey results provide target areas for drilling.

Dam sites

The geologist or the geophysicist will often be able to highlight areas of difficulty during dam site investigations; if there is a fault or soft conditions he will be able to indicate this to the engineer. Sometimes the field worker will state that the structure cannot be built because of the poor foundation conditions. However, it should be remembered that although the foundation may be more expensive to treat, these problems can be overcome by an adequate design.

(i) Buffalo Dam

There is usually a number of interesting problems discovered during the investigations of dam site foundations. Investigations for a suitable site along the Buffalo River indicated three possible sites.

The aim was to indicate which site had the most suitable foundations, and the economics of each site: i.e. which had the widest valley, which had the deepest alluvium, which had the softest rock and so on. The downstream site, McGuffies, contained alluvium filling a wide valley. Seismic refraction work showed the base contours of the valley which was in granite with a number of peaks and valleys some 50 metres below the natural surface. The resistivity information indicated the depths of the near-surface materials such as sands and gravel. These may be useful as materials to construct the dam, e.g. for filter zones or concrete aggregate. Gravity surveys indicated an anomaly on one abutment, and by following the line of this anomaly a large quartz intrusion was discovered on the surface. The intrusion was near the contact of the granite with sedimentary rock which had been metamorphosed. The magnetic survey depicted the subsurface boundary of the metamorphic zone. Bores were used to serve as a control for the geophysical work, and the plots were very good indeed. In 50 metres there may have been a 2-metre difference in levels with various zones. The abutments were also investigated for weathering characteristics - how deeply weathered was the granite - and again contours could be drawn of the weathering of each abutment. This survey could be used as a guide to select target areas for drilling.

The second site further upstream was in a narrow gorge and the refraction survey indicated 40 m of gravel on one flank, above the river gorge. The gravels were a potential leakage path.

The third site, upstream from the second, was finally chosen; here geophysics indicated that the gravels were again on one of the abutments but the base of the gravels which infilled an old valley was above the river bed. Although there was still a potential leakage path it could be clay-blanketed to prevent loss.

Geophysical surveys were successful aids in determining the dam site. In essence the geophysical survey enabled the costs of extensive drilling programs to be defrayed at each site.

Nillahcootie Dam

There was a similar problem on the Nillahcootie dam site. Drilling indicated an infilled river valley on one abutment - this was some 10 metres above the river level, and again a geophysical refraction survey by the BMR indicated the extent of the infilled section so that a clay blanket could be designed to overcome seepage.

An additional refraction survey was needed to detect weathered granite troughs, and this was completed by the Country Roads Board. The spillway was located on a hard granite outcrop but drilling revealed that there were very deeply weathered troughs on this site. It is important that the crest length be adequate to obtain the designed volume passing from the reservoir during high reservoir levels. The use of geophysical methods indicated that there was an island of fresh hard granite with deeply weathered troughs on each side. This enabled the design of an unusual spillway crest which is in the form of a "V" pointing upstream, so retaining the spillway length.

Tarago Dam

A magnetic survey was undertaken at the Tarago site, by a contractor. The dam site is on metamorphosed sedimentary rock with the granite very close by, although there was no certainty of the contact location below the river alluvium. The surface outcrops indicated that the sedimentary rock was very highly weathered, and in addition the magnetic survey established the location of the contact and also indicated that it was limited in width to a hardened series of rock. This survey supplemented by drilling enabled the costing for an excavation to the hard materials. This site was abandoned due to the high cost of excavating large volumes of soft materials and a site 10 km downstream was chosen.

The two difficulties at the upper site were the highly weathered material and cost of its removal, and the possible uneven compaction of the core materials above adjacent zones of hard and soft rock. There could be cracking of the impermeable clay core when the foundation compaction component is changed suddenly, so it is most important to record the changes of the rock hardness across the dam site section.

Bellfield Dam

A refraction seismic survey at Bellfield revealed very soft conditions on one of the abutments. The rock below 5 to 10 metres of scree material had been softened by groundwater which would be concentrated downwards through the unconsolidated materials to the rock mass below. The area of weathered rock was extensive enough to cause concern to the designer. The area of soft rock was stabilised by placing fill upstream of the toe so that there was sufficient weight to prevent a slip failure.

Dartmouth Dam

The seismicity of the Dartmouth Dam area is of interest because of the large size of the dam which is to be 180 metres high. A number of seismographs have been established around the site to measure normal seismic events and any movements as the dam is filling. The seismograph information is being forwarded to Sydney University for assessment. There have not been any movements since the establishment of the seismographs last year.

LITIGATION

The question of responsibility during seismic surveys is often raised because of possible damage from the shots that are fired and the storage magazines which are needed for the explosives. Cases can be given where damage has occurred to market gardens, to power lines, and a variety of subsurface installations. Other instances are where cattle, horses, or poultry are "disturbed". There is also a grass fire hazard during summer. The question is, who bears the cost? Holes which are formed from the shot during the survey - who fills these in? A follow-up team is needed to fill in holes on agricultural lands. Naturally the filled material will sink if it is not properly compacted.

The State Authorities are usually aware of possible litigation after the completion of a seismic survey, but this may not be the case with some other Authorities who work from outside the State. It is a question which needs greater thought on the part of geophysicists. This subject is important, and it is time that guidelines were set to overcome the problem.

CONCLUSIONS

Geophysical survey methods have been proven most successful during the initial phase of investigation programs for determining ground water resources or dam site conditions. At least two areas of weakness remain. The first is an educational problem, for there is lack of understanding between the engineer, geologist, and geophysicist. This would be best overcome at the educational level. Meanwhile close liaison is essential. The second is the need to determine guidelines for responsibility when damage occurs during a survey.

Discussion on D.T. Currey's paper

Question from the floor, speaker unknown

When you say you leave the work and the interpretation of geophysics to the experts, there is a zone of interpretation which lies on the side of geophysics and part which lies on the side of hydrogeology. How do you apportion these interpretations?

D.T. Currey

In geophysics, from a training point of view, there is a large input of advanced mathematics. This maths is often more advanced than that undertaken by a geologist, but an engineer would be qualified in this field. There are of course geologists who complete geophysics as a second subject. I don't think the geologist needs to get involved to any great extent in the interpretation of the results. Sometimes the geologist has to interpret the physical data that the geophysicist gives him, but I think that the hydrogeologist will have a certain idea about an area before he uses geophysical methods, and the results of a geophysical survey can be used to check his ideas. Similarly the geophysicist will obtain the services of a geologist before carrying out geophysical work, to indicate the best methods to use and the most appropriate orientation of the traverses.

Mr Crawford (Darling Downs College of Advanced Education)

Surely the geophysicist's objective is to make a physical model, for example infinite slope or step or whatever, which is consistent with his physical data, and the geologist's objective is to relate the physical model to the geological situation.

E.G. Wilson (BMR)

How do you see the role of the engineer?

D.T. Currey

He is really waiting at an early stage to be fed the information for his design, and his role is really to properly assess the various alternatives which will be evident from the results of the investigation. Quite often he gets several alternatives from the geology and geophysics and he must determine what use he makes of them. The role of the engineer is thus one of an arbitrator and quite often this is a very difficult role for him to fulfill, given his pure engineering training and background.

E.G. Wilson (BMR)

It seems that there is a role for him; perhaps he should be informed of the results of the investigation as it proceeds. He will be considering various alternatives, and if his initial preferences come up against geological problems, he may want ao change in the investigation program to examine other alternatives. He does seem to have some involvement, but he is in a difficult position.

D.T. Currey

I find quite often that involvement is when one receives a design or sketch, and then we need to know the foundation conditions in the various areas where the alternative sites are proposed, whether it be for a tunnel, for siting bores, or for pumping in a dewatering program. The engineer may want to know how deep the weathered material is at a tunnel portal for instance, and in his position he really must believe the information that you give him; quite often this puts the engineer in an unenviable position, especially if the results are complex.

Mr Crawford (Darling Downs CAE)

As a user, do you go along to a geophysicist or a contractor with an open mind about what geology or geophysics is required, or do you suggest what work you want carried out?

D.T. Currey

We generally meet with the geophysicists, tell them the basic engineering problem and the geology, and ask them to suggest the methods and the traverses required, because they have access to all the geophysical techniques. Often the user does not know of the latest techniques; for instance we used a simple depth recorder for traversing across Lake Corangamite but we have never used a sparker system and perhaps did not know about the existence of the instrument at the time. So it is best to leave the selection to the geophysicist.

Mr Crawford (Darling Downs CAE)

Do you ever go into a program with a series of test bores first before calling in the geophysics and thus providing control for the geophysics rather than doing the geophysics in the dark?

D.T. Currey

We always supply relevant borehole data. The geophysicist may require some sort of calibration of his data. I consider that the practice of withholding borehole data to check the geophysics results is quite unfair. Without basic borehole information often the geologist must make an initial rough assessment about the area for the geophysicist.

Question from the floor, speaker unknown

Have you had any experience of tracing movement of groundwater by tracing a particular factor, using geophysics?

D.T. Currey

We have followed the work with interest, particularly BMR's work. We have thought of using the isotope technique, particularly to chase the movement of grout (injected cement). However, we have been told that you can only measure this within a foot of a detector, and this makes it too difficult to plot the grout path through rock. The best method for that is to use different coloured dyes in the grout. BMR did some experiments with tracers in water, and from my recollection they got some strange results. There are difficulties; I am interested in the method, but I am not sure how successful recent experiments have been.

Comment from the floor, speaker unknown

I was thinking of the application of injecting objectionable waste material into an aquifer; this could be one possible means of monitoring the movement of this material.

D.T. Currey

Yes, we are looking at this problem particularly in the western suburbs of Melbourne, where all the industrial wastes are dumped into disused basalt quarries. The Victorian Mines Department monitors the subsurface movements. The BMR in conjunction with the Victorian Mines Department have also used geophysical methods to study the intrusion of salt water into the groundwater basin at Koo-wee-rup, and there is a suggestion that the intrusion is extending a quarter of a mile inland per annum in this area. The geophysics showed this and it was substantiated by drilling, but there is a query on the interpretation at the moment.

Question from the floor, speaker unknown

Are geophysicists interested in applying geophysical methods to groundwater pollution - for instance, sulphide pollution in the groundwater at Mount Isa; CSIRO has been investigating this problem - will geophysics institutions be interested in these problems?

E.G. Wilson (BMR)

I would think that some of the greatest misuse of geophysics has been through inadequate interpretation of data. Geophysical equipment is readily available and we commonly find that non-geophysicists interpret results. Surely the most important part of geophysics is in the interpretation, therefore, I am disturbed when I hear of people interpreting geophysical results without experienced geophysical oversight.

D.T. Currey

I would agree with you. My advice would be in any subject to go to the expert.

Mr Crawford (Darling Downs CAE)

One of the problems in Australia unfortunately is that a lot of the skills of geophysics are taught at schools of pure geophysics with a strong physics and mathematics background and very little emphasis on geology. What is really needed is a person who is trained 50/50 in geology and geophysics. It is a problem to obtain the services of a very good instrumental geophysicist plus geologist in the same person; no existing educational systems in Australia provide this.

D.T. Currey

Similar circumstances exists in a number of fields, for instance, geography departments in Universities may have geomorphologists with no geological training. Of the three universities in Melbourne with geology departments we have three professors, all to some extent geochemists. Why each university does not specialise in different branches of geology I do not know. There is a need to overcome this by proper planning in selection by the administration.

Comment from the floor, speaker unknown

I would like to mention the SA Institute of Technology which has a very large geophysics department. We have 90 students doing geophysics which is compulsory in the geology course.

D.T. Currey

At Melbourne University, we have a geophysics department which is a section of the geology department.

J. Odins (NSW Water Conservation & Irrigation Commission)

I think the previous speaker has put his finger on the problem; when you go to an educational institution under the existing structures, if you want to become an expert then you must specialise in the training stage. As it turns out, you exclude other so-called irrelevant topics, and this is basically where the gap in credibility arises in professions. If for example we take an engineering course at the University of NSW, the first year is common for everybody; in the second year a slight gap is introduced because engineering students do some subjects that geophysicists and geologists do not. This divergence increases in third year and by the time you have graduated perhaps with honours you have separated into your own speciality. By the time you get to the practical application of what you learned at University, then all these other things have to be drawn together by some peculiar process. It involves a lot of time on an individual basis.

D.T. Currey

Co-operation is essential. In our organisation we have five geologists who have to work with 250 engineers. Co-operation is the only successful way to achieve results. There is a very unfair aspect which arises at University levels. An engineer is obliged to undertake a certain amount of supposed basic geology, but a geologist is not expected to study any engineering. The lectures in geology criticise engineers, placing the incorrect emphasis on the reason for a project failure. These failures may well rest with the course structure at Universities.

Mr Crawford, (Darling Downs CAE)

This is the same at the College of Advanced Education, Darling Downs. We always emphasise applied geology, we perhaps are on the side of pure geology, but we still produce people who I think are capable of going out and doing a job, understanding the other point of view, and being able to talk with the client. Quite often if you talk about milligals and gammas the geologist does not know what you are talking about. It is a real communication gap. We give the geologist 120 hours of geophysical training and the greatest thing that we manage to rub off is that the geophysicist's model is in fact a physical model. It is a purely physical model such as a sphere, slab, step, etc., which then has to be translated into a geological context. If the geologist appreciates this then he can do a pretty good job of co-operation with the geophysicist.

D.T. Currey

It is a large arena to work in, but I think we should work towards this sort of thing.

Question from the floor, speaker unknown

Concerning the Koo-wee-rup investigation, for what purpose are geophysical methods being used?

D.T. Currey

Yes the Koo-wee-rup investigation is quite interesting. The Mines Department has been carrying out resistivity and gravity work. There are two aspects of this investigation; one is the salt-water intrusion and the other is the presence of a basalt, some one to two hundred metres below the surface, which is very important as regards recharge of the higher aquifers.

Question from the floor, speaker unknown

What sort of movement does the salt water have?

D.T. Currey

Of the order of a quarter of a mile per year.

B. Farrell, (SA Institute of Technology)

What is the basis for that quarter of a mile figure - is there any geophysical evidence?

D.T. Currey

The evidence is based on one bore below sea level and resistivity records which show a salt wedge protruding inland. A contractor initially carried out some work in the area, but he had difficulty because of the swampland surface salt, and other problems.

Mr Crawford (Darling Downs CAE)

I have seen some infrared imagery carried out by the French, which shows fresh water discharges from coastal aquifers into salt water, the fresh water being colder than the salt water. Has anybody had a look at the Great Australian Bight to see if they could pick up the water seepages into the Great Australian Bight?

D.T. Currey

No, the imagery which I have been showing you is reflected infrared imagery. We have not the thermal equipment ourselves; it is very expensive, some $5000 for an infrared scanner. Professor Ellyett of Newcastle University is working in thermal research, and he has completed marvellous work in tracing fumes from power houses, and hot spots in coal mines etc. We in Victoria have done no work; however, I agree that the thermal imagery may be useful for the Nullarbor problem.

Question from the floor, speaker unknown

What sort of temperature contrasts do you require?

Mr Crawford (Darling Downs CAE)

Very small, less than half a degree.

D.T. Currey

In following the tuna fishing grounds by infrared imagery, they find that plankton follows water with a very critical temperature range, 21 to 22 degrees, I think, and the tuna follow the plankton as it provides them with food. There may not be tuna there but this is an indirect method of finding very good possible tuna fishing grounds. There is interest at the moment in Australia constructing its own ERTS receiving station. It should be realised that the Japanese have one and they fish for tuna off our coastline.

D.L. Rowston (WA Geological Survey)

By "receiving station" do you mean a station which picks up signals direct from the satellite?

D.T. Currey

Yes. There is another instrument, a data platform, $2000, and if the ERTS was to be used in Australia then that would be the best instrument for recording physical data in remote areas. We can set them up for tidal, evaporation, rainfall, any information at all, they send the data to the satellite and receive when the instrument is in view. This gives spontaneous readout of data to the receiving station.

There was one point that I wish to add concerning working with geophysicists, as a user. I have found as a group that they lack responsibility in litigation which may arise from their work. We as a water authority are very conscious of this. As an example, shot-holes in farmers' paddocks have to be filled by the customer, after the geophysicist has walked unconcernedly away. Litigation can be a problem to us, so we maintain fairly good relations with our legal people so that advice can be obtained during the progress of an investigation. Another difficulty in working with geophysicists is the danger to field personnel from explosives and resistivity investigations; care must be exercised in normal field operations.

E.J. Polak (BMR)

The normal situation is that when we work for another organisation the organisation provides untrained staff and the organisation takes the responsibility of cleaning up after operations.

D.E. Leaman (Tasmanian Mines Department)

I would like to comment on your suggestion of monitoring seismic disturbances around dams which are filling with water. This is a common problem in that earthquakes up to magnitude 6 are recorded within the three years after filling and this has to be necessarily a seismically active area. I think that in Lake Kariba and also some dams in India there were some up to 5.5, 5.6; generally these stabilise after a period. The Hydroelectric Commission in Tasmania is doing this also for Lake Gordon, which has an active fault.

D.T. Currey

We have had "shakes" associated with every dam that we have built, say from 16 or 17 metres upwards in depth of water.

Mr Crawford (Darling Downs CAE)

Has anybody thought of monitoring the reciprocal problem, say dewatering of deep aquifers? This does cause some activity in the United States I believe.

D.T. Currey

I don't know of any cases; usually there is some subsidence over a local area.

C. Braybrook (Water Resources Branch, Dept. of Northern Australia)

The explosives ordinance in the Northern Territory is now quite strict about use of explosives, and we have to use a steel magazine; this has severely limited field operations: a large steel magazine has to be transported to the field, unloaded by crane and then returned after field use.

D.T. Currey

On that point I am amazed that the geophysicists can get away with handling explosives in a fairly lax manner. In Victoria on the Lake Buffalo job BMR used a steel magazine on the site.

C. Braybrook (Water Resources Branch, Dept. of Northern Australia)

They are quite strict now, about this magazine rule; previously a hole in the ground with a specially ventilated box was sufficient, but now a steel magazine is required. What will the petroleum exploration people do? At present they use semi-trailer loads of explosives for exploration work. When I questioned the inspector about the ordinance he claimed that we were a special case in using explosives; however, when the ordinance was framed, geophysics was not taken into account, and we still had to abide by the rules of the ordinance.

Question from the floor, speaker unknown

Have you any experience from ERTS with the alkalised waters in southwestern Victoria?

D.T. Currey

You cannot carry out water salinity studies with ERTS. You can recognise sediment in the water, because there is a reflection in the infrared, but with pure water there is absorption of infrared so you can record a blank. If only there were a thermal array on the ERTS, salinity of the water might be detected. The Oceanography satellite which will be launched next year will have all the temperature bands and infrared. The Tyross satellite for weather has up to 12 bands, but the resolution may not be less than 1 km.

ELECTRICAL RESISTIVITY AND ITS INTERPRETATION

N.P. MERRICK

NSW Water Conservation and Irrigation Commission

A B S T R A C T

This paper aims at presenting details of improved field and office techniques for resistivity sounding which enhance the reliability of data acquisition and the credibility of data interpretation. After a brief review of the resistivity method, the Pole-Multidipole (PMD) electrode array is introduced as an alternative to existing configurations. It has several advantages over the Schlumberger method, particularly with regard to the density of field data. The development of resistivity theory is covered briefly with particular emphasis on the application of linear filter theory to an earth model of horizontal layers. A great contrast exists between interpretation methods in common use; mention is made of qualitative and curve-matching procedures, but emphasis is placed on computer modelling and automatic inversion. The logic behind resistivity inversion in the transform domain is presented and program performance is described. Examples of automatic interpretations illustrate the capabilities of the resistivity sounding method.

INTRODUCTION

The electrical resistivity method is widely used in geophysical exploration for groundwater; in some parts of the world, it is the most important method. The principles of the method were developed at the time of the First World War but little use was made of the method before 1930. The Illinois State Geological Survey, in 1935, was perhaps the first body to include routine resistivity surveys in their hydrogeological investigations (Buhle & Brueckman, 1964). Because of the urgent need for domestic and industrial water after the Second World War, West Germany also chose to use resistivity; by 1953, it had been applied to about 200 groundwater projects (Hallenbach, 1953). In 1958, the Netherlands put the method to routine use and a report (Van Dam & Meulenkamp, 1967) shows that about half of the state had been covered by 1967. But, in most parts of the world, the method has been slow in gaining acceptance; perhaps this has been caused by the difficulties of quantitative interpretation, adequate methods for which did not become available until the mid-1960s. In New South Wales, the Water Conservation & Irrigation Commission has been using the method only since 1972.

Resistivity may be regarded as a geophysical property of matter which depends on the more fundamental properties of porosity, water content, water salinity, and lithotype. The presence of ions dissolved in groundwater has a controlling influence on resistivity because it is the ions which provide the mechanism of conduction in most earth materials. In unconsolidated aquifers, clay content is perhaps as important in establishing the true resistivity of the medium (Hackett, 1956).

The resistivity method is an application of Ohm's Law and is based on the fact that all materials offer resistance to the passage of electrical current. Current is injected into the ground by connecting a power supply across two metal electrodes; two other electrodes are used to measure the potential difference created on the surface of the earth. A distinction is made between the resistivity sounding and resistivity traversing methods by the way in which the electrode array is moved for successive readings. The sounding method detects vertical changes in resistivity by increasing the spacing between current electrodes; in traversing, the electrode spacings are fixed, and lateral variations in resistivity are indicated by shifting the entire array to adjacent ground.

The quantity measured in the field is called apparent resistivity. It has no physical significance other than its complex dependence on the true resistivity and thickness of each layer. The unit of measurement is the ohm-metre, which may be regarded as the resistance of a cube of ground with a side dimension of one metre. Clays have a low resistivity of about 10 ohm-metres while sands and gravels range from about 1 ohm-metre (for salt-water) up to 300 ohm-metres (for fresh-water). Fresh sedimentary, igneous, and metamorphic rocks are invariably resistive, but shale is conductive.

Many electrode arrays are possible, but all are based on a standard four-electrode system. The symmetrical Schlumberger array is most common, with two outer current electrodes and two inner potential electrodes. Readings are taken each time the outer electrodes are moved apart so that current penetrates deeper into the ground. Apparent resistivities are calculated at each spacing and are plotted on a bilogarithmic scale. A complete survey usually consists of a line or grid of spot soundings so that vertical and lateral trends are defined quantitatively.

During the interpretation phase, mathematical complexity often limits the choice of earth model to a sequence of horizontal layers of constant resistivity. Variations from this simple model are frequently recognised on field curves, but usually, only qualitative allowances are made. Although electrical anisotropy may be investigated in the field, it is often neglected and depth overestimates may result. The resistivity method has an inherent limitation in its ability to resolve thin layers. It is sensitive, not to a layer's absolute thickness, but to its relative thickness; the ratio of thickness to depth. A layer is said to be suppressed if it has no expression on a field curve. Perhaps the most important problem inherent in the resistivity method is equivalence (Koefoed, 1969). This means that many different layering configurations may give rise, within experimental error, to identical field curves. It arises from the fact that, for thin layers, the method is sensitive either to the thickness-resistivity product (for resistive zones) or the thickness-resistivity ratio (for conductive zones). Although absolute depth estimates are ambiguous under such conditions, without geological control, the thickness-resistivity product is a useful parameter because it is linked with yield.

The resistivity method is an inexpensive, operationally simple method, suited ideally to detailed investigations for depths less than about 300 m. Equipment need not be sophisticated, but an inadequate power supply limits the maximum depth of investigation. A three-man crew is usually able to do four soundings per day where the depth of interest is about 100 m; this rate is equivalent to a linear coverage of about 1 km per day.

Resistivity soundings have found application in a host of geological environments throughout the world. Most common is the application to unconsolidated sediments where the thickness and distribution of alluvial aquifers are important. Details of bedrock relief are often sought, especially in the search for buried valleys. Of particular merit has been the application of the method to the detection of freshwater/salt-water interfaces, either in coastal areas (Flathe, 1955), arid environments (Morris, 1964), or, more recently, in regions of mining and industrial pollution (Stollar & Roux, 1975). Some success has been reported of groundwater salinity estimates from surface resistivity measurements, especially in Europe (Volker & Dijkstra, 1955). Hard-rock applications are less well documented, but investigations of dyke-impounded water and fractured or weathered rock are common (Enslin, 1955).

It must be stressed that electrical anomalies will occur only when lithological boundaries have a definite resistivity contrast. Frohlich (1974) cites a case where no contrast existed between a thick freshwater gravel and a brine-saturated limestone. He accounted for the lack of contrast by porosity compensation. Hallenbach (1953) and Buhle & Brueckmann (1964) all found more success with conductive bedrock than resistive bedrock. Krulc & Mladenovic (1969) and Zohdy (1973) experienced masking problems with both low- and high-resistivity layers which effectively hid important deeper layers. The importance of control cannot be underestimated; without it, we can provide a geoelectric section but not an accurate geologic section. A mandatory part of any resistivity survey is the performance of soundings against bores or over outcrop to see how different lithologies behave electrically.

THE POLE-MULTIDIPOLE METHOD

The Water Conservation & Irrigation Commission uses a modification of the Schlumberger method known as the Pole-Multidipole (PMD) method (Merrick, 1974). It uses an asymmetrical electrode array which consists of one mobile current-electrode, one stationary remote current-electrode and a number of potential-electrodes (see Figs. 1 & 2). Each pair of potential electrodes gives a resistivity sounding; in essence, we obtain a number of soundings not at the one spot, but over a distance of some tens of metres.

Certain inadequacies of the Schlumberger method of sounding provided the motivation for the new technique. In particular, the Schlumberger method provides no check on the reliability of each element of data. If a measurement error occurs, it may go unrecognised and be treated as true depth information which could result in an erroneous interpretation. The PMD method provides a check on the consistency of field data measured on different dipoles. Measurement errors are obvious and the reliability of measured data is improved.

With n potential-electrodes a total of n(n-1)/2 soundings is possible; e.g. for n=5, total = 10. In the field, we measure only (n-1) of these; the rest can be obtained by superposition back in the office.

The data provided by each dipole are placed into one of two groups:

(i) Schlumberger data... $\ell/L \simeq 0$

(ii) Pseudo-Schlumberger data... $\ell/L \neq 0$

The majority of data satisfies the first condition and may be treated as being equivalent to Schlumberger data for interpretation purposes. The rest of the data provides useful information and may be used for a more thorough interpretation, but this is seldom necessary.

In other asymmetrical arrays, the remote electrode is placed at "infinity", which may be of the order of 5 to 10 times the maximum distance between the measuring point and the primary current-electrode. But the PMD

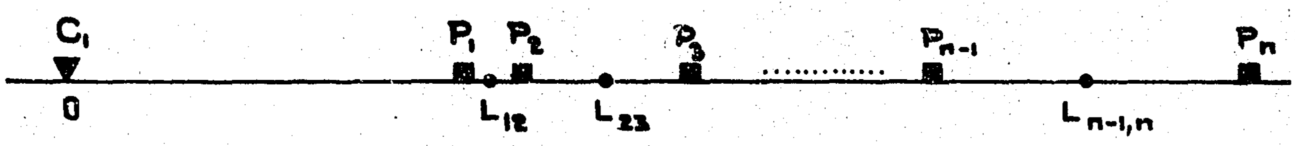


FIGURE 1: Pole – Multidipole (PMD) Array; C_2 is offset from the centre of the dipole spread

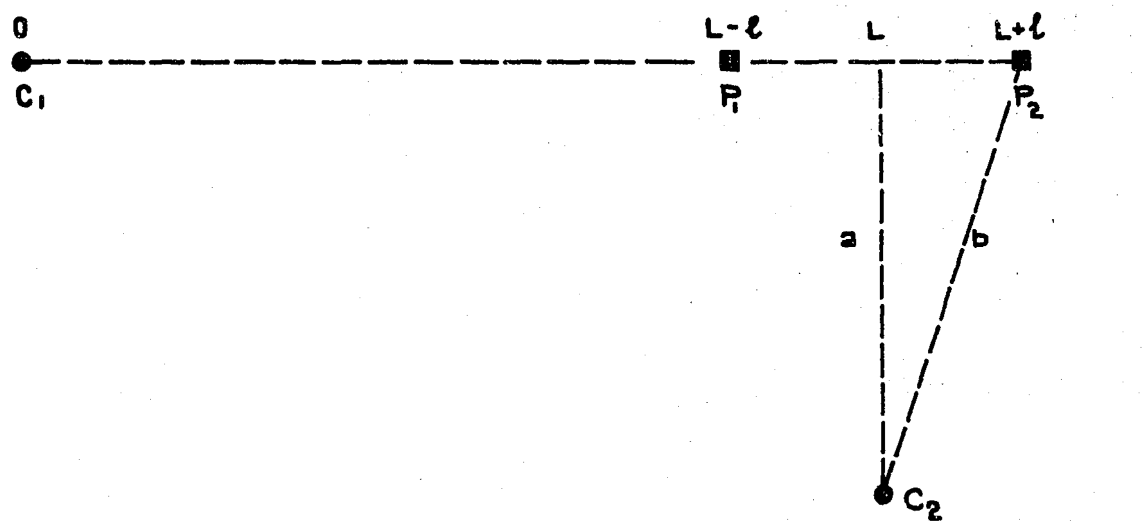


FIGURE 2: Plan view of simplest PMD (Half-Schlumberger) array

system will tolerate a remote-electrode distance of the same order as the maximum mobile current-electrode distance. This is due to the stationary nature of the potential-electrodes.

Sample theoretical curves are shown in Figure 3.

NOTE:

(i) $\ell \leq 0.2$ gives a Schlumberger curve;

(ii) for $\ell > 0.2$, PMD curves are to the right of the Schlumberger curve;

(iii) the PMD curves approach the Schlumberger curve as $L \to \infty$;

(iv) all PMD curves have the same layer-resistivity sequence;

(v) when $L = \ell$, $R_a = R_1$.

The PMD method requires little alteration in field procedure. In the way of equipment, necessary additional components are a dipole-selector switch and a "takeout" cable for the potential-electrode connections. If uncommutated D.C. is used, separate S.P. buck circuits are necessary for each dipole.

A sounding can be conducted by two people: one on the mobile electrode, the other on the measurements. Normally we have a third person to speed up the layout of electrodes and cables, to do the apparent resistivity calculations and to monitor two of the dipole curves as the sounding progresses.

Sample field curves are shown in Figure 4. They were obtained with an array of 6 potential-electrodes, a remote-electrode distance of 200 m, and maximum mobile-electrode distances of 300 m (Fig. 4 a) and 500 m (Fig. 4 b). Here, five dipole soundings were recorded in the field and another ten may be obtained by superposition. The data for all 15 dipoles, which obey the Schlumberger condition, are shown in Figure 5 for comparison with Schlumberger soundings at the same site. The expansion was along the same line as the PMD pot-spread, so there is some difference in actual current direction. Note the difference in sampling rate between the two methods and the dilemma posed by the kinks in the Schlumberger curve: are they to be accepted as true depth information, or are they due to observational errors or electrode effects?

The PMD method reduces electrode effects by having only one mobile electrode and by leaving potential-electrodes undisturbed for an entire sounding.

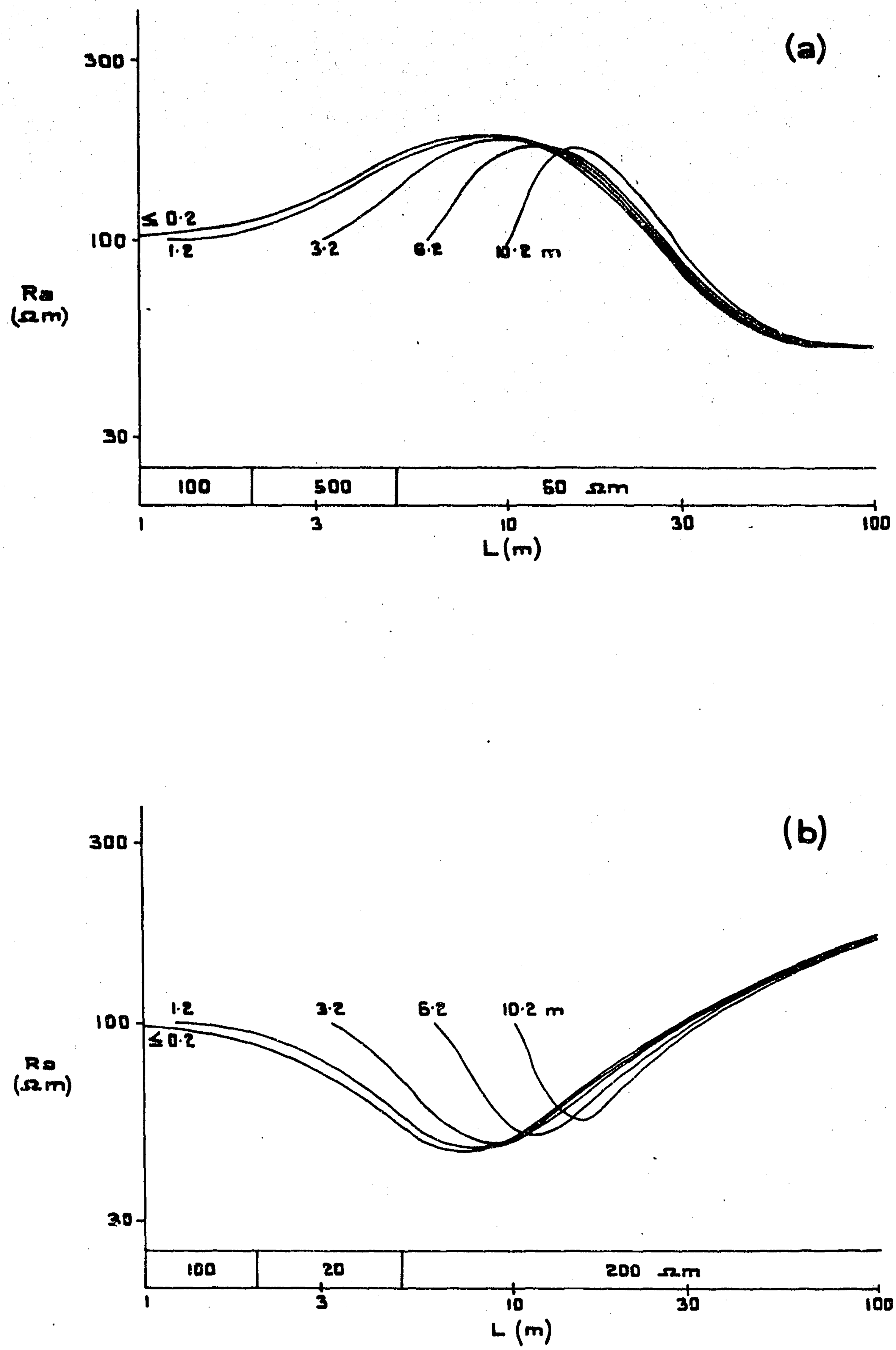


FIGURE 3 : Theoretical PMD curves for each dipole (parameter ℓ) of a six-pot spread for arbitrary models (a) and (b)

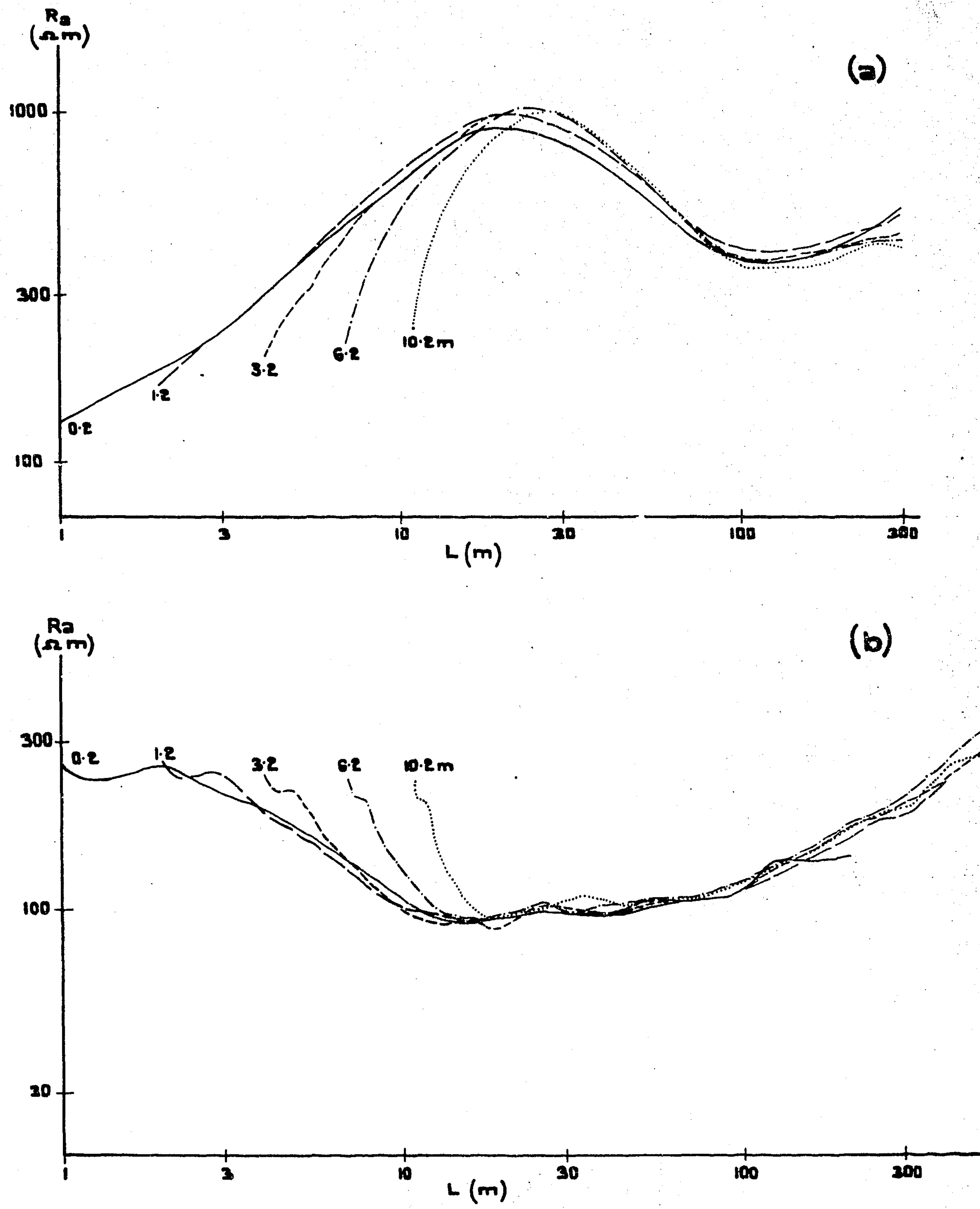


FIGURE 4: Field PMD curves for each dipole (parameter ℓ) of a six-pot spread for cases (a) and (b)

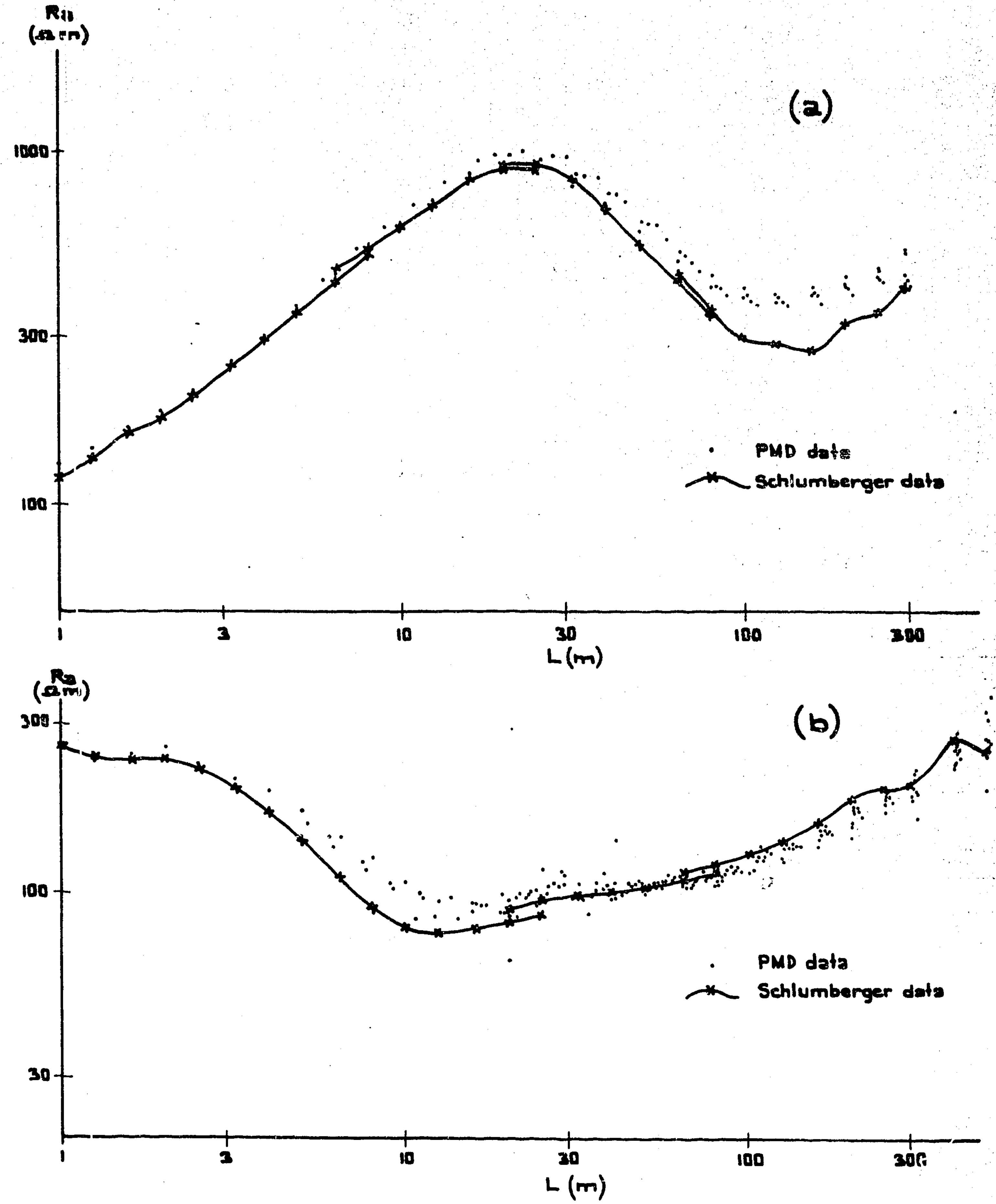


FIGURE 5 : Field comparison of PMD and Schlumberger data for cases (a) and (b)

Mobile current-electrode effects may occasionally be recognised on PMD curves. When they occur, they affect all dipole curves but the effect shows at different current-electrode distances. Figure 6 shows how four pots respond to an earth-crack system. With true depth information, each dipole curve is affected in the same way at the same current-electrode distance.

Possible remote-electrode effects are shown on Figure 7. Figure 7(a) shows how the distance of the remote-electrode affects the shape of a theoretical curve. If ignored, the second-layer thickness will be under-estimated. If the remote-electrode is too close, evidence is usually provided by departures between the various dipole curves. Figure 7(b) shows an example where negative apparent resistivities are actually recorded. It should be stressed that this data is still meaningful and may be interpreted by matching against theoretical curves generated by a computer.

Potential-electrode effects are recognised as constant-percentage offsets between different dipole-curves. They are familiar on conventional Schlumberger surveys and occur at each expansion of the potential-electrodes. They occur at every reading using the Wenner system, but they cannot be separated from true depth information. An example is shown in Figure 8 which suggests that offsets of about 50% are possible. The source of the effect is attributed to the presence of local inhomogeneities in the ground surface. Note how separate interpretations of the dipole curves would give different absolute resistivities for the same layer. If potential-electrode effects are suspected, they should be normalised to the same surface resistivity. Page (1968) found that low surface resistivities in the top 5-10 m gave rise to interpreted resistivities less than the true values.

Quantitative interpretation of the data may be done in two ways:

(i) complete curve-match by computer of each dipole curve,
(ii) standard interpretation of equivalent Schlumberger data.

The first option is illustrated by Figure 9, but this approach is tedious. The second option requires that the data be used as a basis for a representative Schlumberger curve. The procedure we follow is shown as follows:

(i) field measurements of voltage and current are input to a computer and the apparent resistivities for each dipole are calculated and plotted (Fig. 10);

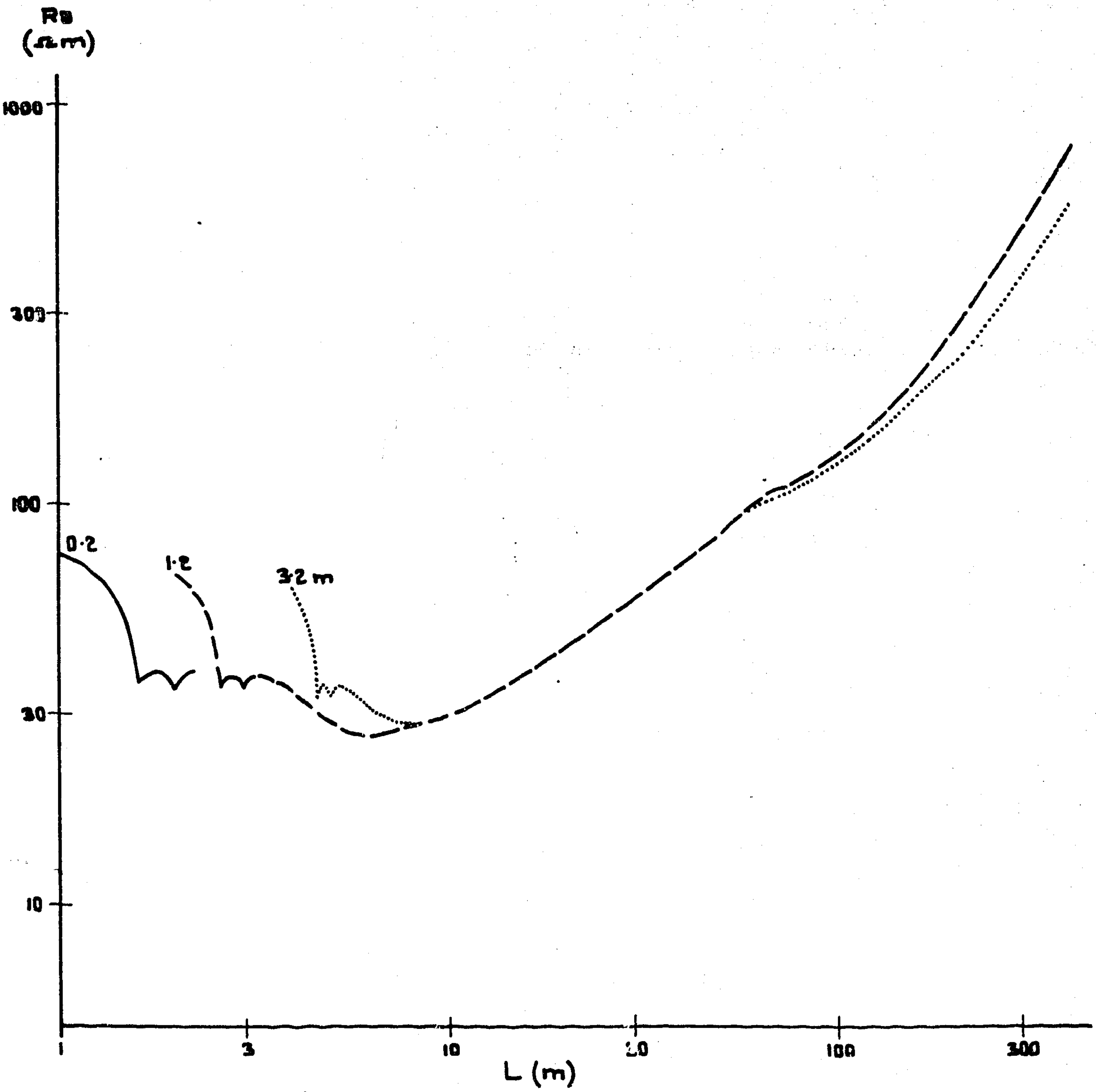
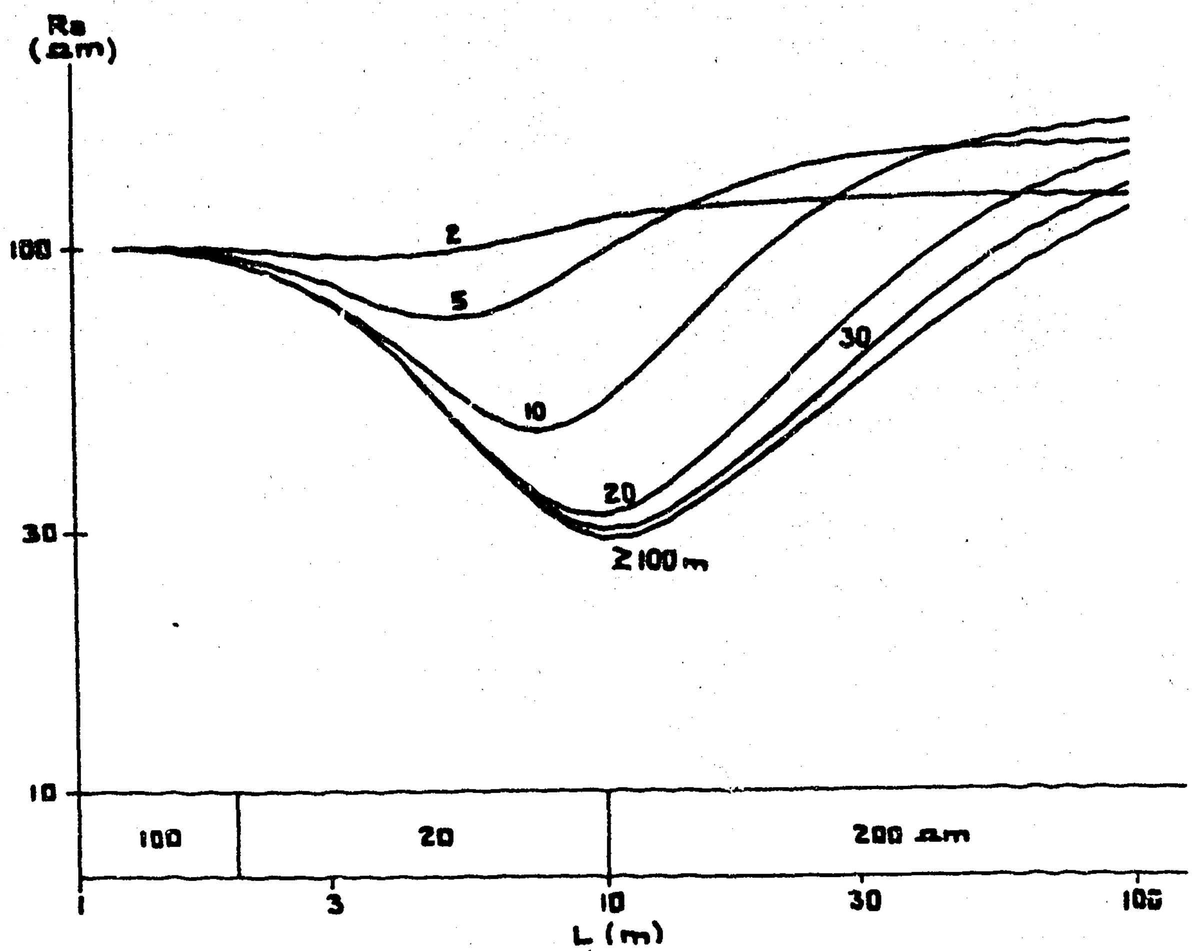
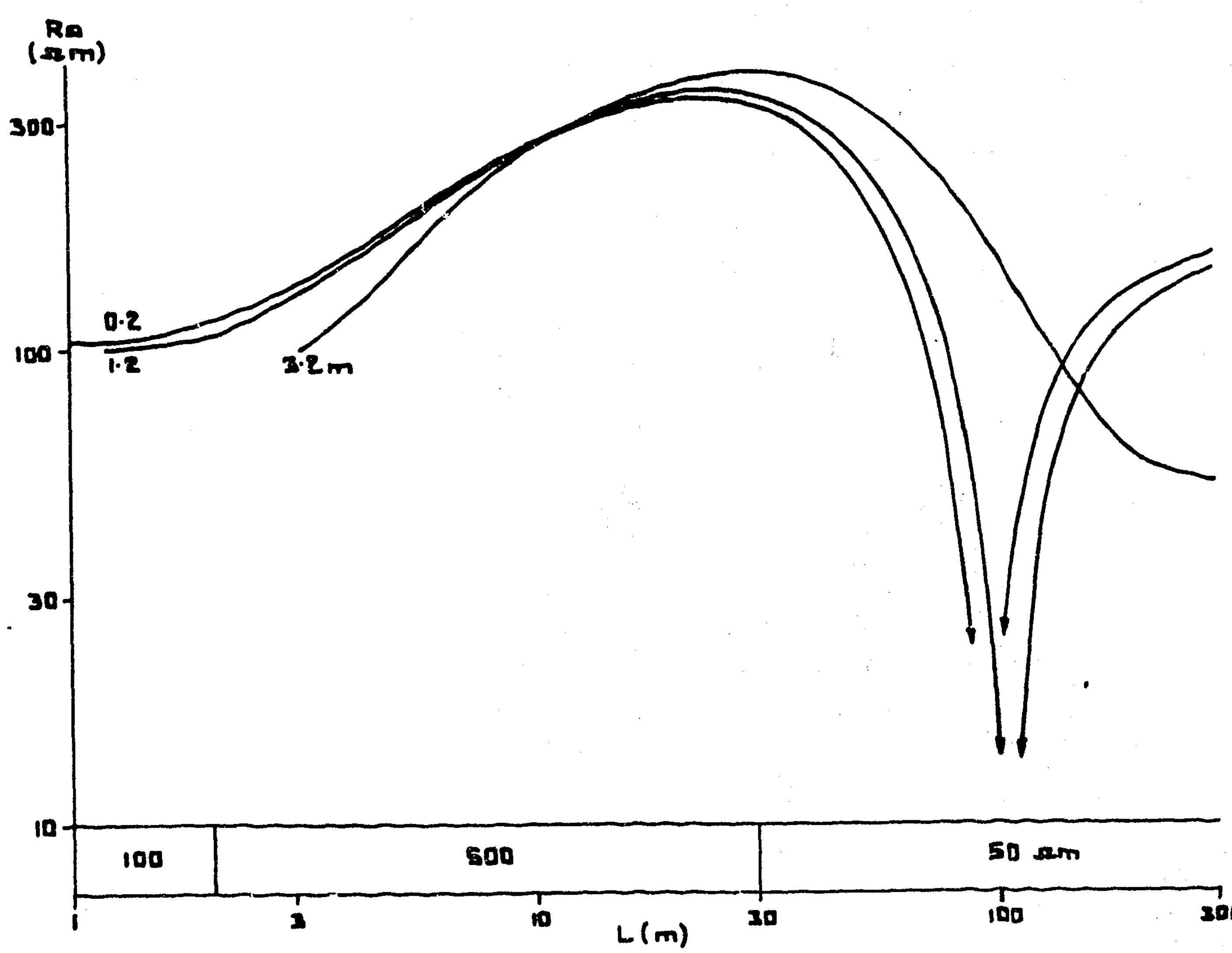


FIGURE 6 : Mobile-electrode effect on three PMD dipoles (parameter ℓ) due to an earth-crack system



<u>FIGURE 7(a)</u>: Theoretical PMD curves with remote-electrode effect on dipole P_{13} (ℓ = 1·2 m) of a four-pot spread (length 6·4 m); parameter is remote-electrode distance (in metres).



<u>FIGURE 7(b)</u>: Theoretical PMD curves with remote-electrode effect on each dipole (parameter ℓ) of four-pot spread (length 6·4 m); remote-electrode distance is 30 m.

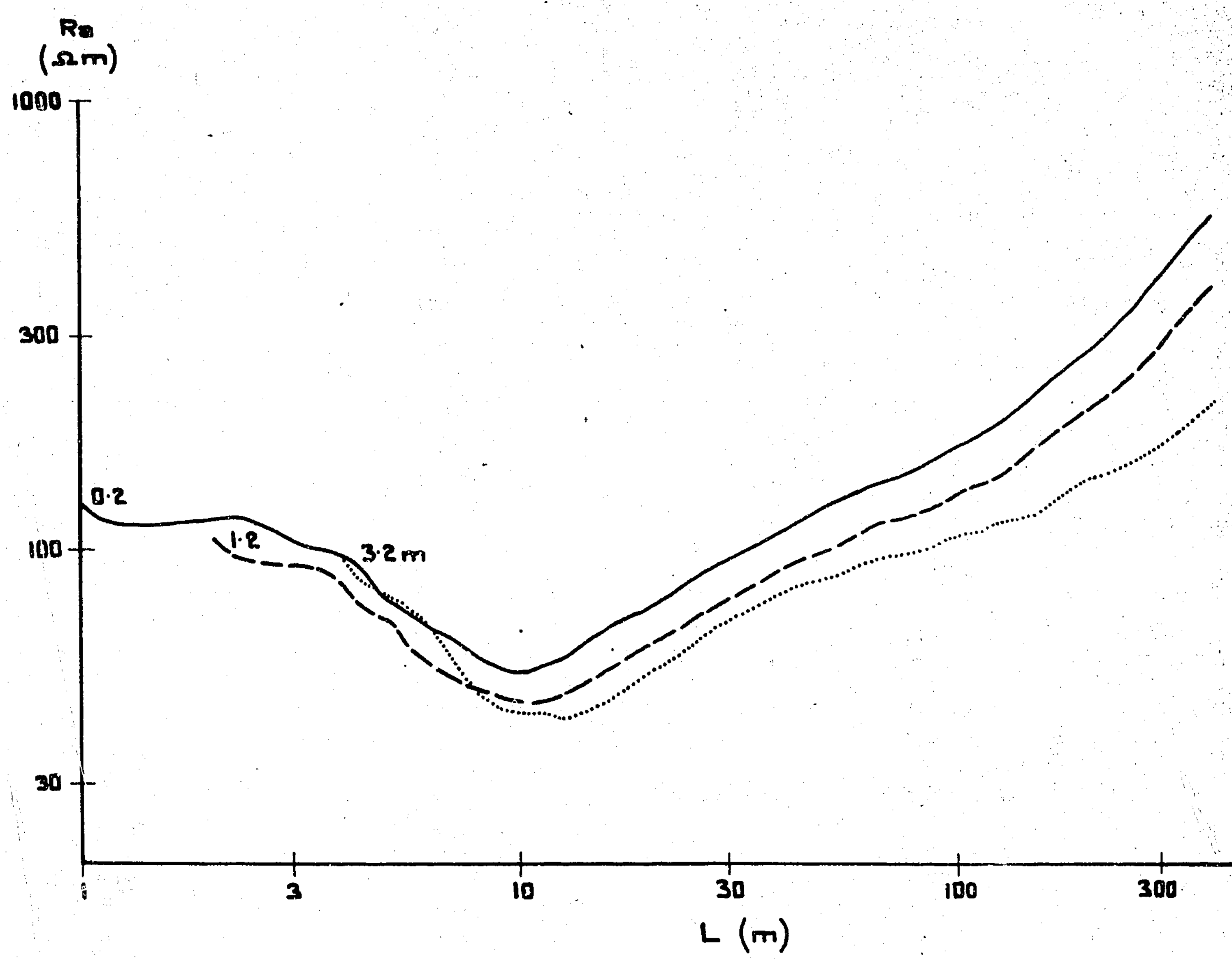


FIGURE 8 : Potential-electrode effect on three PMD dipoles (parameter ℓ) due to inhomogeneities near pots

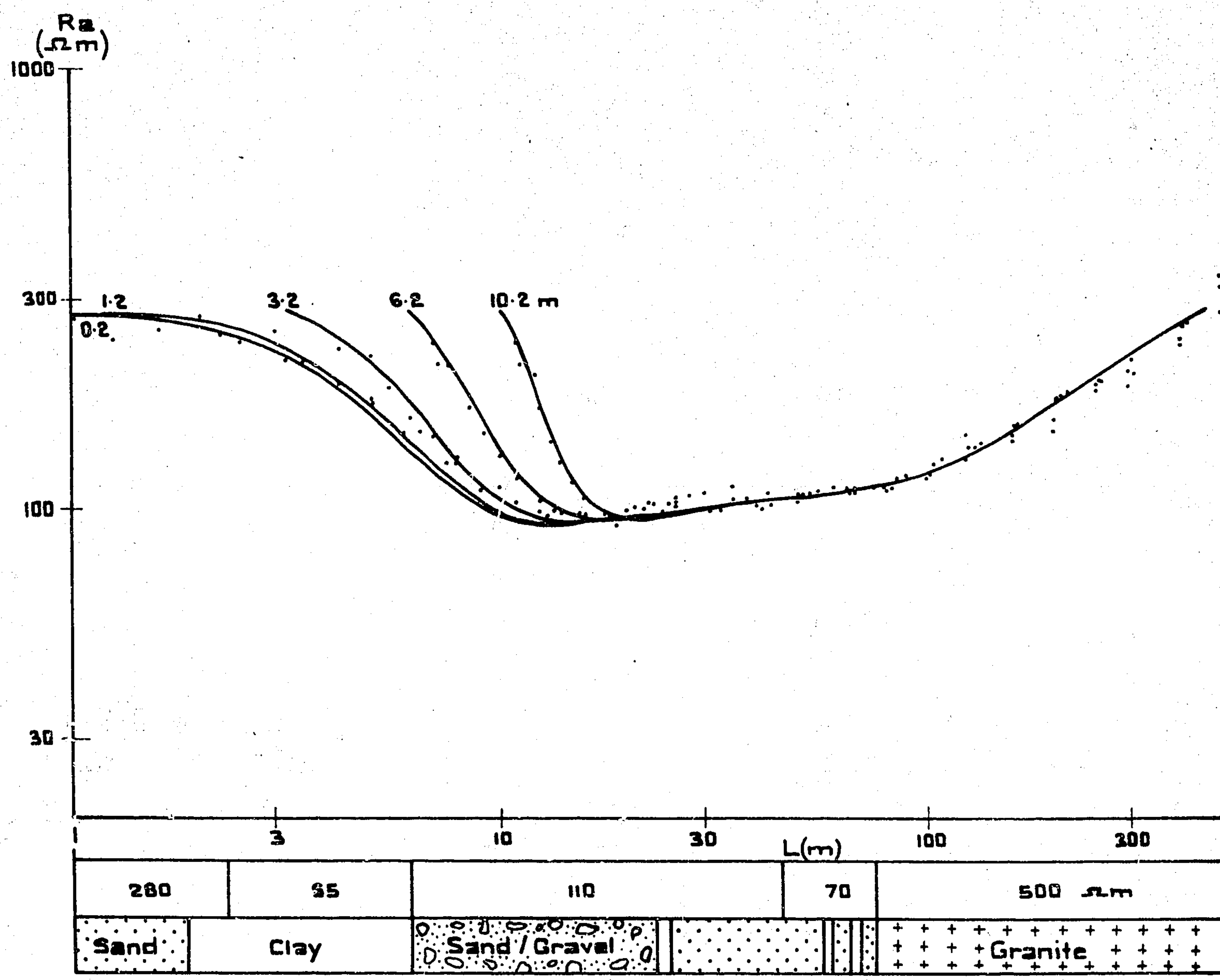
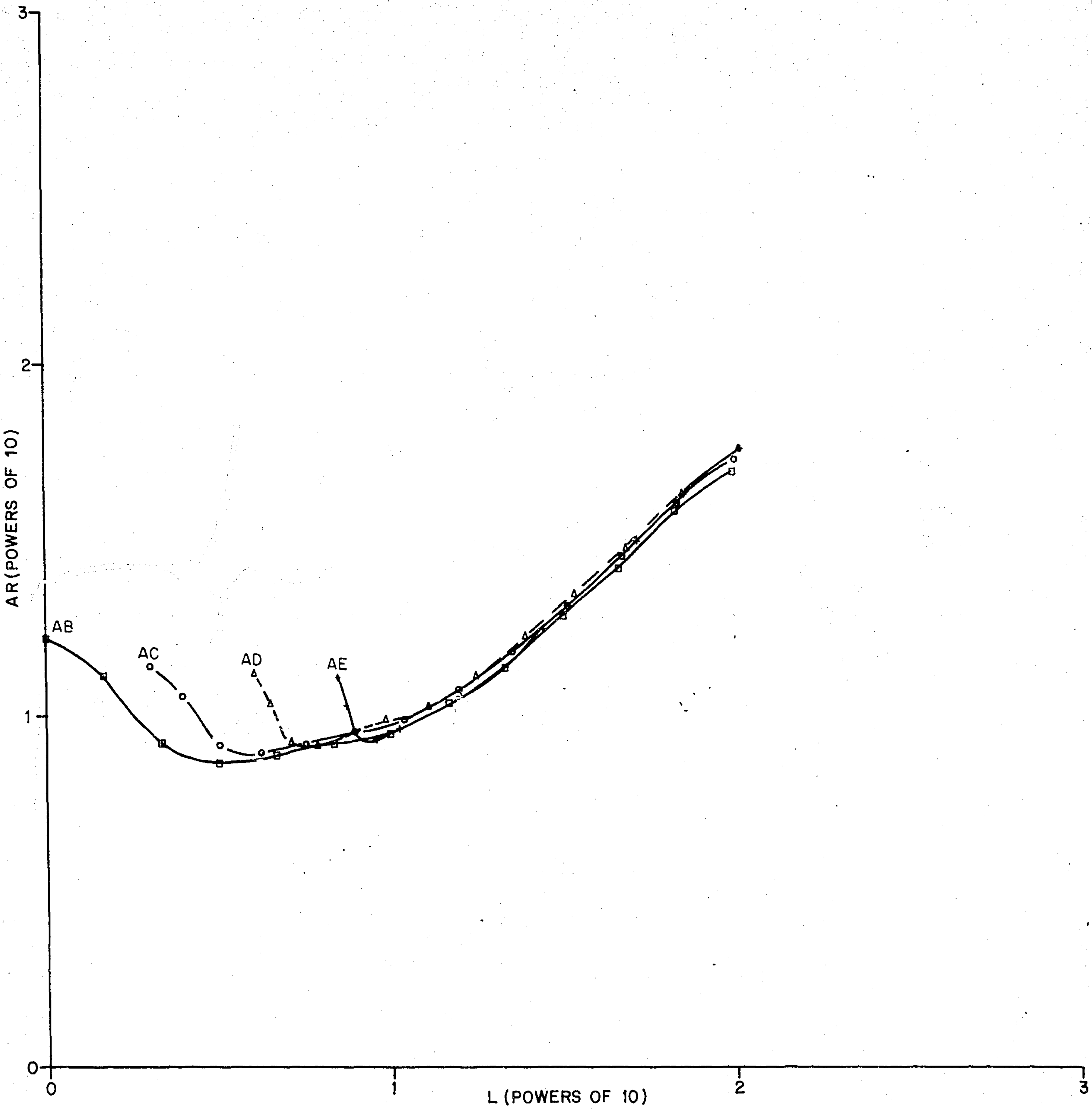


FIGURE 9 : Complete PMD curve-match on each dipole (parameter ℓ) of a six-pot spread; with comparison of interpreted depth-section and simplified bore-section.

Fig. 10



MAJOR DIPOLES

(ii) apparent resistivities are also calculated by computer for all other possible dipoles; all Schlumberger-equivalent data are then plotted (Fig. 11);

(iii) with the shape of the major dipoles in mind, a smooth curve is drawn through the all-dipoles data to give the representative curve (Fig. 12);

(iv) this curve is the basis for subsequent interpretation; it is digitised and stored as a data-file on disc.

The PMD method has several advantages over the Schlumberger system:

(i) there is only one mobile electrode, so current-electrode effects are reduced;

(ii) the potential-electrodes are not disturbed during a sounding, so electrode effects are held under control;

(iii) the remote current-electrode need not be at "infinity" which is convenient operationally;

(iv) Two people can conduct a sounding;

(v) the method is only slightly slower than the Schlumberger system but the amount of data acquired per unit time is much greater;

(vi) the density of data provides a mechanism for self-checking the reliability of data;

(vii) lateral effects are often recognised and are not misconstrued as depth information;

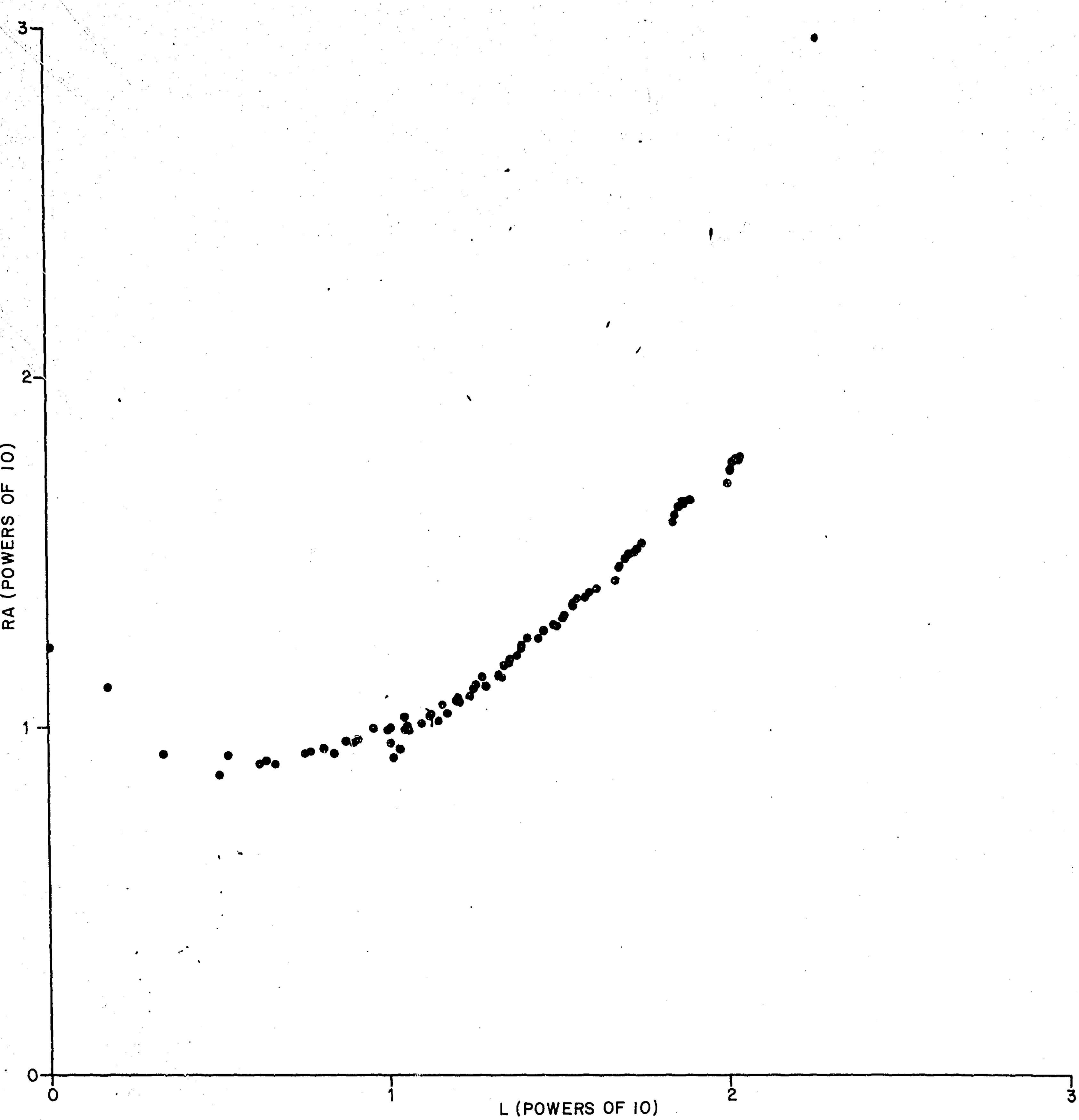
(viii) the final output of the method is a sounding curve which is theoretically equivalent to a Schlumberger curve; conventional interpretation procedures may be retained;

(ix) asymmetrical arrays permit soundings in restricted areas, e.g. corners.

The disadvantages of the method are:

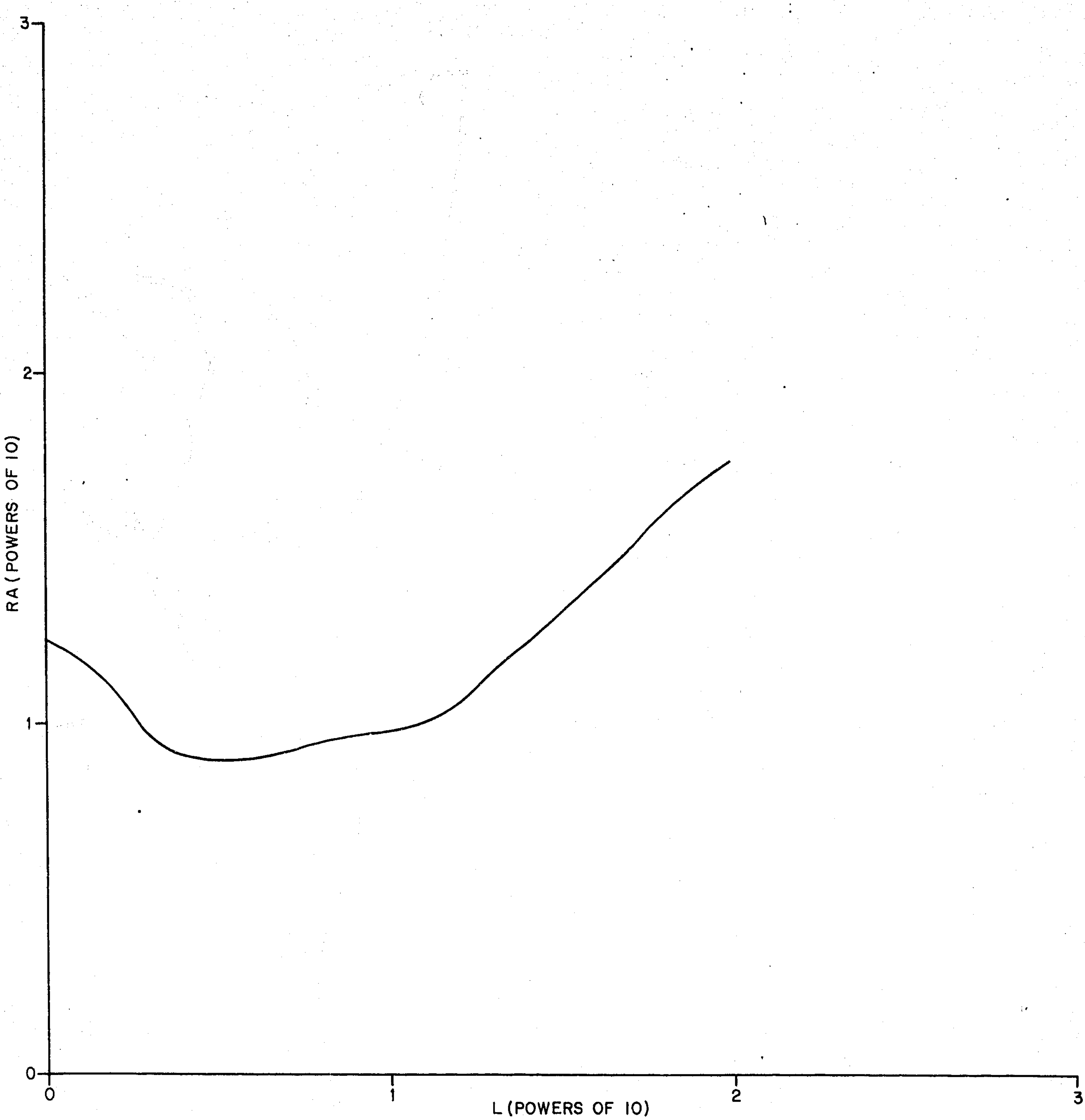
(i) remote-electrode effects are not noticed until the sounding is almost finished; if rectified they occasion some time delay; often, they cannot be avoided;

(ii) mobile current-electrode effects are not recognised at large distances;



ALL DIPOLES

Fig.12



(iii) potential-electrode effects need to be adjusted before lumping together the data from all dipoles;

(iv) the current direction varies as the sounding progresses, making anisotropic investigation difficult;

(v) the large amount of data does not suit manual reduction.

In summary, the Pole-Multidipole method gives very reliable field data by using a string of potential-electrodes and by taking multiple readings at each position of the current-electrode. If the field data are known to be reliable, then interpretational confidence should increase.

RESISTIVITY THEORY

The development of theory is summarised in Figure 13. From this we see that the electrical resistivity method is an application of Ohm's Law which describes how, in an applied electric field, the conductivity of a medium determines the current density within the medium. Conductivity is the reciprocal of resistivity, and in a uniform earth, the current density can be expressed by the current passing through the surface area of a hemisphere. If the earth is not uniform, the same resistivity formula is useful in showing the departures from uniformity, and the concept of apparent resistivity is introduced.

More fundamentally, however, resistivity theory stems from Maxwell's Law for the electric field strength under steady-state conditions which suggests that the field strength may be regarded as the gradient of an electric potential. This equation, in combination with the charge conservation condition, leads to the basic differential equation which describes how the electric potential varies in an arbitrary resistivity distribution where conductivity at each point varies with direction.

If the earth can be divided into regions of constant conductivity, then the basic differential equation reduces to Laplace's equation, which was solved by Stefanesco et al. (1930) for the special case of multiple horizontal layers, each of which is assumed to be laterally homogeneous and isotropic. For any nominated earth model, theoretical apparent resistivities can, in principle, be found by the evaluation of an integral which depends on a Bessel function and a kernel function; the Bessel function depends on

DEVELOPMENT OF RESISTIVITY THEORY

Ohm's Law $\underset{\sim}{J} = \sigma \underset{\sim}{E}$, $R_a = \frac{2\pi r^2}{I} |\underset{\sim}{E}|$

Charge Conservation $\underset{\sim}{\nabla} \cdot \underset{\sim}{J} = 0$

Maxwell's Law $\underset{\sim}{\nabla} \times \underset{\sim}{E} = 0$, $\underset{\sim}{E} = -\underset{\sim}{\nabla} V$

Differential Equation $\underset{\sim}{\nabla} \cdot \sigma \underset{\sim}{\nabla} V = 0$

Laplace's Equation $\nabla^2 V = 0$

Stefanesco & Schlumbergers (1930)

$$V(r) = \frac{IR_1}{2\pi} \left[\frac{1}{r} + 2\int_0^\infty \Theta_n(\lambda) J_0(\lambda r) d\lambda \right]$$

$$\frac{R_a(r)}{R_1} = 1 + 2r^2 \int_0^\infty \Theta_n(\lambda) \lambda J_1(\lambda r) d\lambda$$

Mooney et al. (1966)

$$\Theta_n(\lambda) = \sum_{N=1}^{\infty} Q(N) e^{-2N\lambda}$$

$$\frac{R_a(r)}{R_1} = 1 + 2r^3 \sum_{N=1}^{\infty} Q(N) (4N^2 + r^2)^{-3/2}$$

Koefoed (1970)

$$\Theta_n(\lambda) = \frac{T(\lambda)}{2R_1} - \frac{1}{2}$$

$$R_a(r) = \int_0^\infty T(\lambda) \lambda r^2 J_1(\lambda r) d\lambda$$

Ghosh (1971)

$$T(\lambda) = \int_0^\infty R_a(r) \frac{J_1(\lambda r)}{r} dr$$

$$T_m = \sum_j a_j R_{m-j}$$

$$R_m = \sum_i b_i T_{m-i}$$

the distance from the current source, and the kernel function depends on the layer thicknesses and resistivities. The oscillatory nature of the Bessel function makes numerical integration inefficient.

An approximate method of calculation was given by Mooney et al. (1966) by expanding the kernel function as a series and then integrating analytically term by term. The approach is suitable for digital computers, but the rate of convergence of the series is slow for large distances from the current source and for large resistivity contrasts. Any values of layer resistivity are permitted but layer depths must be integral multiples of the thickness of the top layer. To be able to model layers of arbitrary thickness, the top layer has to be very thin and total depths must be large. But computer storage and run-time increase with total depth, so the method is not well suited to smaller computers.

A new approach to the problem was heralded by Koefoed (1968, 1970) when he expressed the kernel function in terms of a resistivity transform function which he evaluated from a nominated earth model by a recursion formula. Ghosh (1971a) expressed the transform function as a Hankel inversion of the apparent resistivity formula and showed this to be a convolution integral, thereby showing that the apparent resistivity and the resistivity transform are linearly related. By taking Fourier transforms of the output, input, and filter functions he was able to write

$$F(f) = G(f)*H(f)$$

The filter spectrum H(f) was found from known input and output functions and the coefficients of the linear filter were sampled from the sinc response

$$H(f)\ \Delta x \qquad \ldots \quad |f| \leq \frac{1}{2\Delta x}$$

at the same sampling interval, Δx, as used on the original apparent resistivity data. By the use of these forward filter coefficients, field apparent resistivities could quickly be converted to equivalent resistivity transforms.

In a later paper, Ghosh (1971b) solved the inverse case in a similar way. He expressed the apparent resistivity formula as a convolution integral and derived inverse filter coefficients which quickly converted resistivity transform data to apparent resistivity transform data.

The significance of this work is that theoretical sounding curves can now be calculated very quickly; an earth model is specified, theoretical resistivity transforms are calculated by Koefoed's recursion formula and these are converted to theoretical apparent resistivities by Ghosh's inverse digital filter. The logic is easy to program and requires very little computer-storage; e.g. a 10-layer case requires storage for about 100 variables. Program run-time is also independent of depth magnitudes and resistivity contrasts.

Ghosh used a sampling interval of ($\ln 10$)/3; O'Neil (1975) has shown this to give inadequate accuracy for conductive layers when the resistivity contrast with the overlying layer exceeds twenty. By choosing an interval of ($\ln 10$)/6 he overcame the problem. His new filters consist of 25 points for the forward case and 20 points for the inverse case.

Linear filters are now available for Schlumberger and Wenner arrays, for each of the dipole-dipole arrays, and for electromagnetic sounding with horizontal and vertical loops (Ghosh 1971a, 1971b; Das et al., 1974; Koefoed et al., 1972; O'Neill, 1975).

INTERPRETATION METHODS

Despite the operational simplicity of the resistivity method, "the problems of interpretation are among the most difficult in geophysics" (Frohlich, 1973). Because of mathematical complexity, the method has fallen prey to a number of empirical procedures which are purported to give simple short-cut solutions (Moore, 1945; Barnes, 1952; Sanker Narayan & Ramanujachary, 1967); they have no theoretical basis, are invariably erroneous, and have done much harm to the credibility of the resistivity method (Muskat, 1945; Mooney, 1954; Keller, 1968; Greenhalgh, 1974).

An initial qualitative appraisal is always made of field curves. This identifies the number of electrical layers, approximate layer resistivities and depths, and, in the light of known geology, suggests what the causative lithologies might be. If adjacent soundings exist, curve features are correlated to show continuity and lateral variation. If it is the objective of the survey to recommend a test bore site, then a simple qualitative analysis will often suffice. It is here, too, that we identify curve anomalies which we know cannot be caused by horizontal layers and which are not interpreted quantitatively at the present state of the art (Zohdy, 1969).

The most widely used method of quantitative interpretation is curve-matching. Here a field curve is directly compared with previously drafted type-curves which have been computed for known earth models. The model for the best match is assumed to be the solution. The process is tedious for

3-layer curves and is unworkable for more than three layers. For multilayers, partial curve-matching is used. Here, the first three layers of the field curve are matched with a type-curve; then, the first two layers are combined into an electrically equivalent layer and the next three-layer section is matched. The process repeats until the entire field curve is matched. The problems with this approach are that the accuracy worsens for more layers and there is no check that the interpreted model would give a theoretical curve similar to the field curve.

The next step in interpretation is to bypass the curve-matching stage and find trial-and-error solutions with the aid of a computer. The interpreter guesses an earth model and the computer calculates the corresponding theoretical curve. If the match is not good enough, the interpreter tries another model and compares results again until a good match is obtained. This method is suited ideally to a small on-line computer with plotting facilities; with experience, one can usually obtain a good fit in about 6 trials. At the Water Conservation & Irrigation Commission, we have a program to do computer modelling of this kind. A digitised resistivity sounding is called off the disc, interpolated, and plotted as a continuous curve. A request is made at the teletype for a trial model; after this is specified, the theoretical sounding is calculated by linear filter theory and is plotted as point data on the same graph as the field curve. Another trial model is requested and another set of theoretical data points is plotted, with a symbol different from the first set. We also have programs for plotting field curves in stack-form or profile-form at a number of convenient scales.

Logically, it would seem better to use the computer to make modifications to an initial earth model. Vozoff (1958) was first to attempt this by using both the Newton method and the steepest descent method for iteration. He made digital comparisons in the transform domain but he used a kernel function as defined by Slichter (1933) which was formulated recursively by Sunde (1949) for a nominated earth model. Meinardus (1970) used the same kernel function and he described in detail the conversion from field apparent resistivity data to the field kernel function by numerical Gaussian integration. He used the Marquardt (1963) method for iteration which combines the better aspects of both Newton's method and the steepest descent method. Inman et al. (1973) achieved automatic inversion in the apparent resistivity domain by application of the basic formulation of Mooney et al. (1966) and by using Newton's method for iteration. The method I wish to describe here makes comparisons in the resistivity transform domain, relies on the basic formulas of linear filter theory, and uses the Marquardt method for iteration. The advantages of working in the transform domain are speed, ease of computation, and the fact that transform curves are of the same numerical order as resistivity curves, the two are linearly related, and the transform function is independent of the electrode array but depends only on layer thicknesses and resistivities. The main disadvantage of the transform domain in conjunction with linear filter theory is that the field apparent resistivity curve has to be extrapolated at both ends. Another problem is that the measure of fit in the transform domain shows little consistent connection with the measure of fit in the apparent resistivity domain.

The last-mentioned advantage leads to the development of a method of automatic interpretation which is valid for any electrode array. The logic of this suggestion is shown in Figure 14.

RESISTIVITY INVERSION

Suppose we have m observations $\underline{T}^*=(T_i^*)$ (i=1,2,...,m) over an n-layer earth with k(=2n-1) parameters $\underline{P}^*=(P_j^*)$ (j=1,2,...,k). A trial model $\underline{P}=(P_j)$ gives theoretical data $\underline{T}=(T_i)$. The aim of the inversion procedure is to find the model vector $\underline{P}$ which minimises the sum of squares

$$\emptyset = \sum_{i=1}^{m} (T_i^* - T_i)^2 = \| \underline{T}^* - \underline{T} \|^2$$

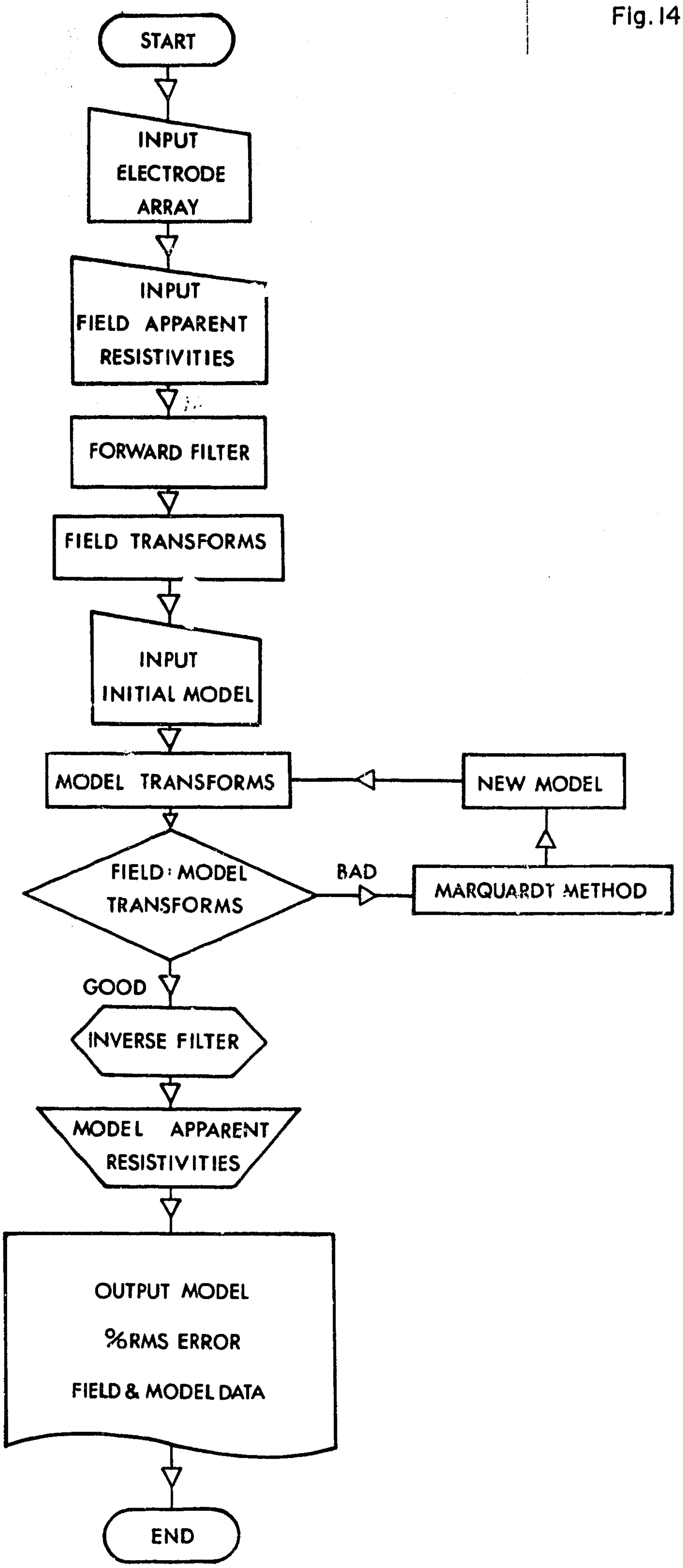
If we write $\underline{\Delta P} = \underline{P}^*-\underline{P}$ and $\underline{\Delta T} = \underline{T}^*-\underline{T}$ then we can linearise the problem by defining a matrix $\underline{\underline{A}}$ which takes the parameter correction vector and maps it into the vector of differences between observed and calculated values:

$$\underline{\underline{A}} \; \underline{\Delta P} = \underline{\Delta T}$$

This is equivalent to linearising the transform function by a Taylor Series expansion about a trial model:

$$T_i(\underline{P} + \underline{\Delta P}) = T_i(\underline{P}) + \sum_{j=1}^{k} \left(\frac{\partial T_i}{\partial P_j} \right) \Delta P_j$$

Fig. 14



FLOW CHART FOR AUTOMATIC INVERSION

FOR ANY ELECTRODE ARRAY

where the elements of matrix $\underline{\underline{A}}$ are recognised as transform derivatives:

$$a_{ij} = \frac{\partial T_i}{\partial p_j}$$

Because the problem is really non-linear, we cannot find a simple inverse $\underline{\underline{A}}^{-1}$ which gives $\underline{\Delta P}$ from $\underline{\Delta T}$. But we can find a generalised inverse $\underline{\underline{A}}^{+}$ such that

$$\underline{\Delta P} \simeq \underline{\underline{A}}^{+} \underline{\Delta T}$$

This can be found rigorously by an eigenvalue decomposition of matrix $\underline{\underline{A}}$ and is the method used by Inman et al. (1973). Alternatively, $\underline{\underline{A}}^{+}$ may be approximated by the Marquardt method, commonly known as the damped least-squares method. Marquardt (1963) showed that $\emptyset$ is minimised by $\underline{\Delta P}$ where $\underline{\Delta P}$ also satisfies this equation:

$$(\underline{\underline{A}}^{T} \underline{\underline{A}} + \varepsilon \underline{\underline{I}}) \underline{\Delta P} = \underline{\underline{A}}^{T} \underline{\Delta T} \qquad \ldots \varepsilon > 0$$

He proved that as $\varepsilon \rightarrow \infty$, $\| \underline{\Delta P} \|^{2} \rightarrow 0$; that is, there must always exist an ε which gives a better model estimate.

An efficient algorithm for finding the generalised inverse is due to Golub as described by Jennings & Osborne (1970). It relies on the factorisation of the matrix $\underline{\underline{A}}$ into an orthogonal matrix and another matrix ($\underline{\underline{R}}$) with all elements below the leading diagonal zero. The ε-appendage is applied not to the original matrix $\underline{\underline{A}}$ but to the factor matrix $\underline{\underline{R}}$ so as to minimise computational effort for different trial values of ε. The matrix $\begin{bmatrix} \underline{\underline{R}} \\ \hline \varepsilon \underline{\underline{I}} \end{bmatrix}$ undergoes orthogonal factorisation and $\underline{\Delta P}$ is found by back-substitution. Jennings & Osborne give FORTRAN subroutines for each stage.

The transform function is defined recursively as shown on Figure 15. Note that transform derivatives with respect to each layer parameter are necessary for matrix $\underline{\underline{A}}$ and these may also be expressed recursively as shown.

The flow chart of Figure 16 shows the detailed logic of automatic inversion by the Marquardt method. If the current model vector is not adequate, then the new model is given by

Fig. 15

Transform Function:

$$T_{i+1} = \frac{T_i + T'_{n-i}}{1 + \frac{T_i\,T'_{n-i}}{R^2_{n-i}}} \qquad (i=2,3,\ldots\ldots n-1)$$

$$\text{where} \quad T'_{n-i} = R_{n-i}\left[\frac{1-\exp\left(\frac{-2E_{n-i}}{U}\right)}{1+\exp\left(\frac{-2E_{n-i}}{U}\right)}\right]$$

$$T_2 = R_1\left[\frac{1+k_{12}\exp\left(\frac{-2E_1}{U}\right)}{1-k_{12}\exp\left(\frac{-2E_1}{U}\right)}\right]$$

$$k_{12} = \frac{R_2-R_1}{R_2+R_1}$$

Transform Derivatives:

$$\left(\frac{\partial T_{i+1}}{\partial p_j}\right) = a_1\left(\frac{\partial T_i}{\partial p_j}\right) + a_2\left(\frac{\partial E_{n-i}}{\partial p_j}\right) + a_3\left(\frac{\partial R_{n-i}}{\partial p_j}\right) \qquad (j=1,2,\ldots\ldots,2n-1)$$

$$\text{where} \quad \left(\frac{\partial T_2}{\partial p_j}\right) = c_1\left(\frac{\partial E_1}{\partial p_j}\right) + c_2\left(\frac{\partial R_1}{\partial p_j}\right) + c_3\left(\frac{\partial R_2}{\partial p_j}\right)$$

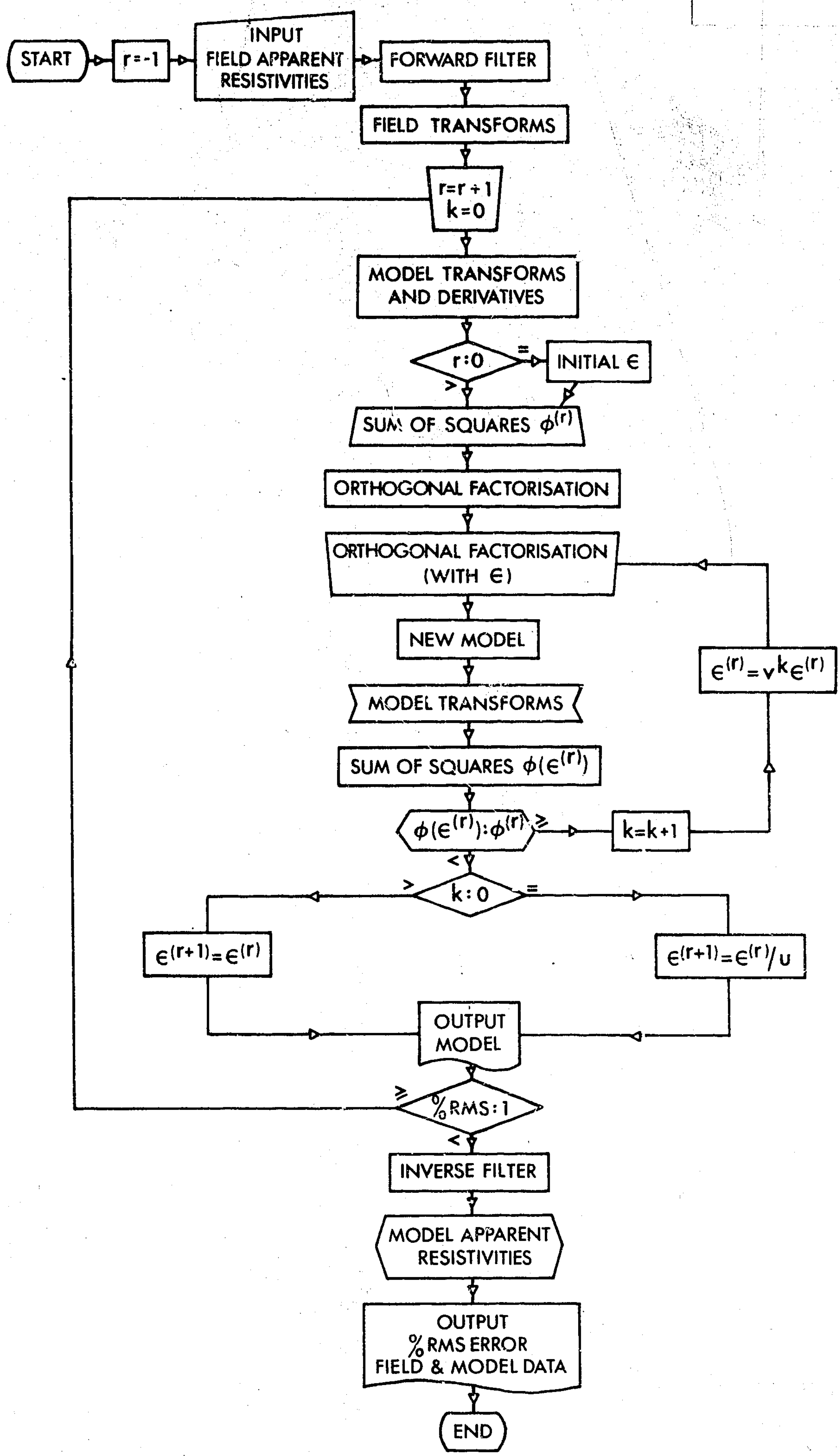
$$(p_j) = (E_1, E_2, \ldots\ldots, E_{n-1}, R_1, R_2, \ldots\ldots\ldots, R_n)$$

$$\left(\frac{\partial p_k}{\partial p_j}\right) = \delta_{jk}$$

$$\underline{a}, \underline{c} = \text{functions}\,(T_i, T'_{n-i}, p_j)$$

RESISTIVITY TRANSFORM FUNCTION AND ITS DERIVATIVES

Fig. 16



FLOW CHART FOR AUTOMATIC INVERSION
BY THE MARQUARDT METHOD

Record No. 1976/108

$$\underline{P}^{(r+1)} = \underline{P}^{(r)} + \underline{\Delta P}^{(r)}$$

The measure of "goodness-of-fit" is the root-mean-square percentage error and is defined this way:

$$\%RMS = 100 \left[\frac{1}{m} \sum_{i=1}^{m} \left(\frac{T_i^* - T_i}{T_i^*} \right)^2 \right]^{\frac{1}{2}}$$

An example of the program output is shown in Figure 17. Note the output of field and theoretical apparent resistivities, the measure of error, the interpreted model, and monitors of pseudoanisotropic parameters.

Figure 18 shows visually how the inversion program proceeds from an initial model to the final solution in a small number of iterations. This example is for a theoretical curve where the parameters chosen for the initial model were in error by 50% to 200%; after the fifth iteration, the errors range from 0.03% to 0.62%.

The program is being run on a Digital Equipment Corporation PDP 8/E computer with external disc storage, a Calcomp 565 drum plotter and a high-speed printer. Available storage is 12K 12-bit words. The program is written in OS/8 BASIC language using 6-digit single precision. The amount of storage required varies with the number of model layers and the number of field data; with a model of 10 layers, and 20 data points, the program requires storage of about 1500 variables. The 8/E assigns three words to each variable, so that the storage requirement is 4.5K plus text of about 4 pages. The machine is relatively slow in execution, and run-time averages about one minute per iteration. Solutions are invariably found in less than ten iterations, often three or four.

To account for equivalence, the program includes the option to fix any layer resistivity or thickness. Fixed layer resistivities have been found to be successful but fixed thicknesses give intolerably slow convergence. Suppressed layers are usually removed automatically from a trial model by being reduced to zero thickness or by being assigned an adjacent layer's resistivity.

The following examples of automatic interpretations are intended to illustrate the accuracy of depth estimates from resistivity and the problems of resistivity contrast, suppression and equivalence. (Note that the depth scale is logarithmic in each example).

CR75D2

(P)

RMS %ERROR = 3.77388

I	L	RA-FIELD	RA-MODEL	%ERROR
1	1	129	125.492	-2.71952
2	1.47	72	69.25	-3.81949
3	2.15	65	64.3938	-0.93267
4	3.16	70.5	75.9299	7.70195
5	4.64	91	96.2625	5.78291
6	6.81	123	120.869	-1.73216
7	10	151	143.739	-4.80866
8	14.7	157	158.358	0.864744
9	21.5	157	160.592	2.28817
10	31.6	153	152.125	-0.571966
11	46.4	138	138.121	0.0874281
12	68.1	117	120.463	2.95987
13	100	99	96.8318	-2.19014
14	147	75.5	71.059	-5.88214
15	215	55	58.0802	5.60045
16	316	66.5	66.8618	0.544095

INTERPRETED MODEL ...

--- 0

RES = 810 THICK = 0.28

--- 0.28

RES = 50 THICK = 1.79

--- 2.06

RES = 330 THICK = 3.94

--- 6

RES = 131.55 THICK = 55.58

--- 61.59

RES = 20 THICK = 82.48

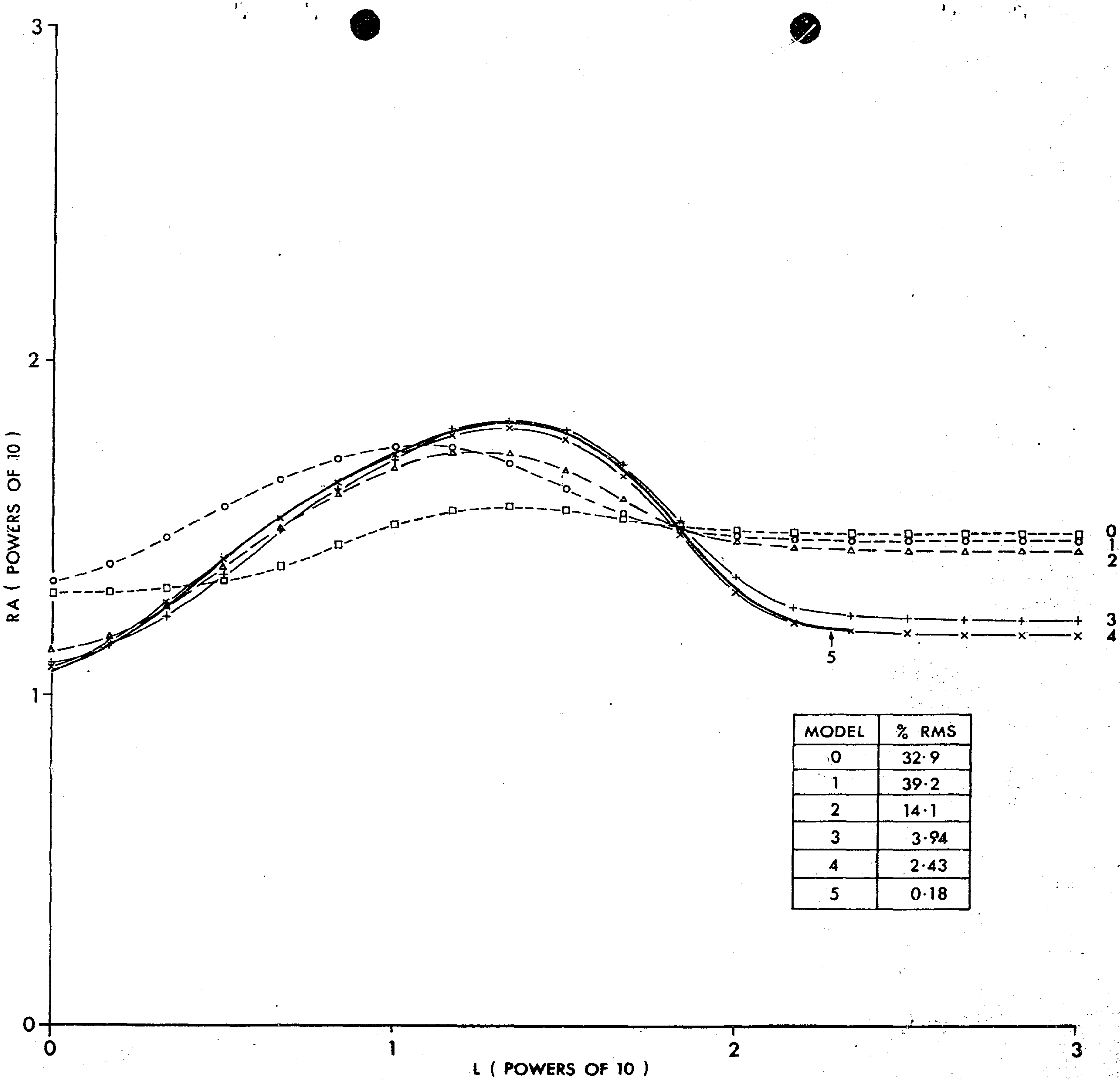
--- 144.06

RES = 1000.27

LAYER	T=THICK*RES	S=THICK/RES
1	223.046	0.00033996
2	89.3074	0.035723
3	1300.92	0.011946
4	7311.85	0.422512
5	1649.52	4.1238

TRANS. RESISTANCE: T = 10574.6
LONG. CONDUCTANCE: S = 4.59432
MAX. DEPTH: ANISO*Z = 220.416 ANISO = 1.53001
BULK RESISTIVITY: RM = 47.9758

FIGURE 17 **Sample Output of Automatic Inversion Program.**



MODEL	% RMS
0	32·9
1	39·2
2	14·1
3	3·94
4	2·43
5	0·18

Fig. 18

The resistivity sounding curve of Figure 19 gives considerable stratigraphic information by detecting five distinct zones: soil, silt, clay, aquifer and bedrock. There is no resolution within the aquiferous zone; its bulk resistivity is, however, "unique" with the important consequence that the bedrock depth estimate is also unique. The clay zone exhibits electrical equivalence and is responsible for a range of alternative solutions. The seismic refraction method gives three distinct zones: unsaturated sediments, saturated sediments, and bedrock; the bedrock depth estimate is poor but, it must be stressed, this is an exception rather than the rule.

In Figure 20 we have the unusual case of a clay (being sandy and dry) which is more resistive than the underlying aquifer. Again, there is no resolution within the aquiferous zone except for some resistive sediments immediately above bedrock which are expressed on the field curve but are very difficult to identify automatically. Without this resistive zone, bedrock depth estimates are erroneous.

Because the sounding of Figure 21 was performed 100 m east of a bore, caution must be exercised in comparing the known lithology with the resistivity interpretations. The bedrock depth estimate is good but there is some doubt as to the equivalence of the near-surface clay; if it is not equivalent, then the method has responded to a bulk clay/gravel/sand zone.

Figure 22 shows the drastic effect of pseudoanisotropy on estimated bedrock depths when several layers are interpreted as a single layer. An automatic method has difficulty in resolving minor field curve flexures without intervention, so it is often necessary to force layers into the inversion program and maintain some control over the interpretation. When this is done, the depth estimate improves considerably.

Poor resistivity contrasts within the alluvium are responsible for the almost-featureless curve of Figure 23. Pseudoanisotropy again gives large errors in bedrock depth estimates.

CONCLUSION

The resistivity method is an inexpensive and operationally simple method which is suited ideally to detailed investigation of depths less than about 300 m. Equipment need not be sophisticated, but an inadequate power supply limits the maximum depth of investigation. A three-man crew can do four soundings per day where the depth of interest is about 100 m; this rate is equivalent to a linear coverage of about 1 km/day.

Fig. 19

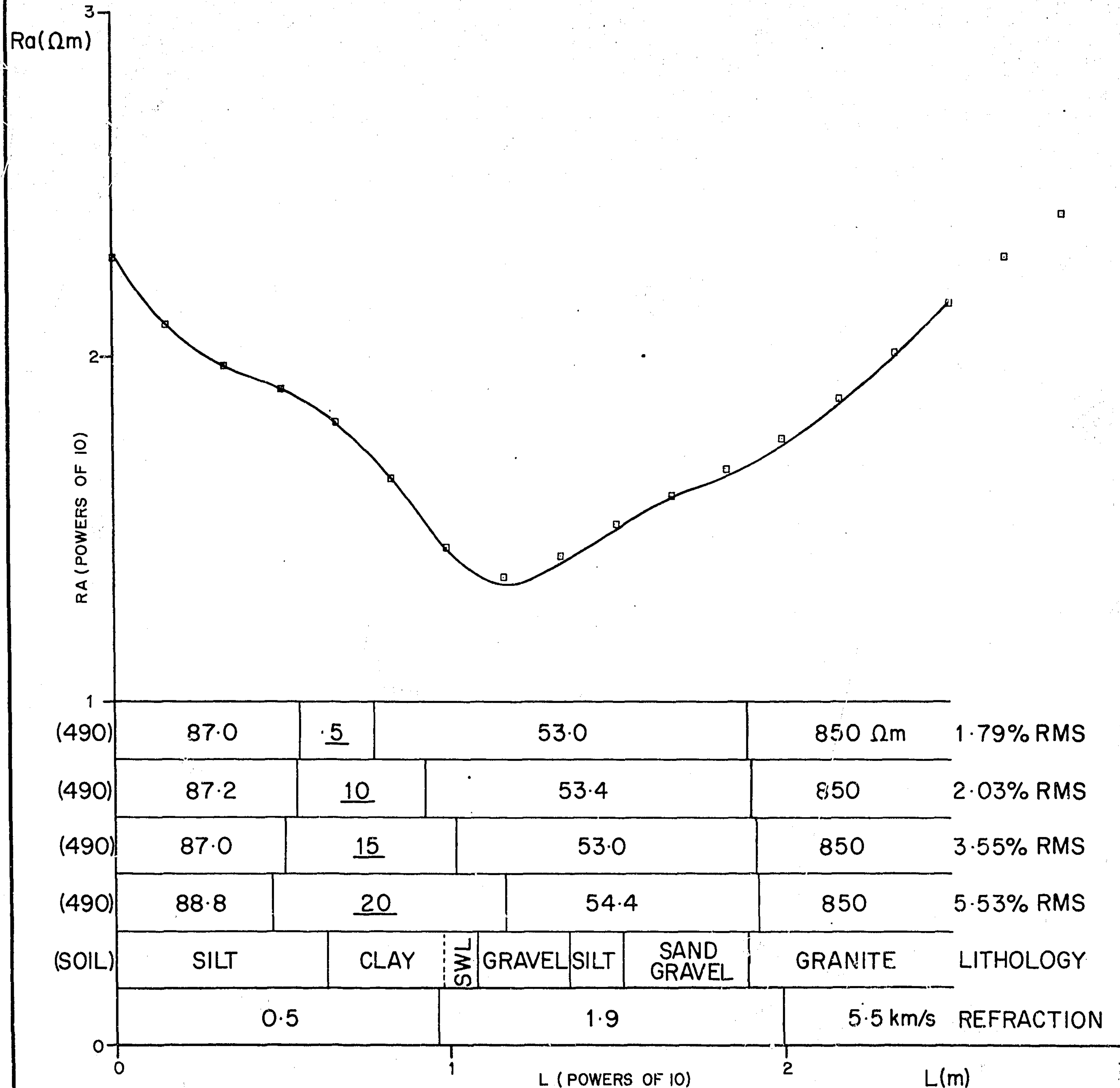
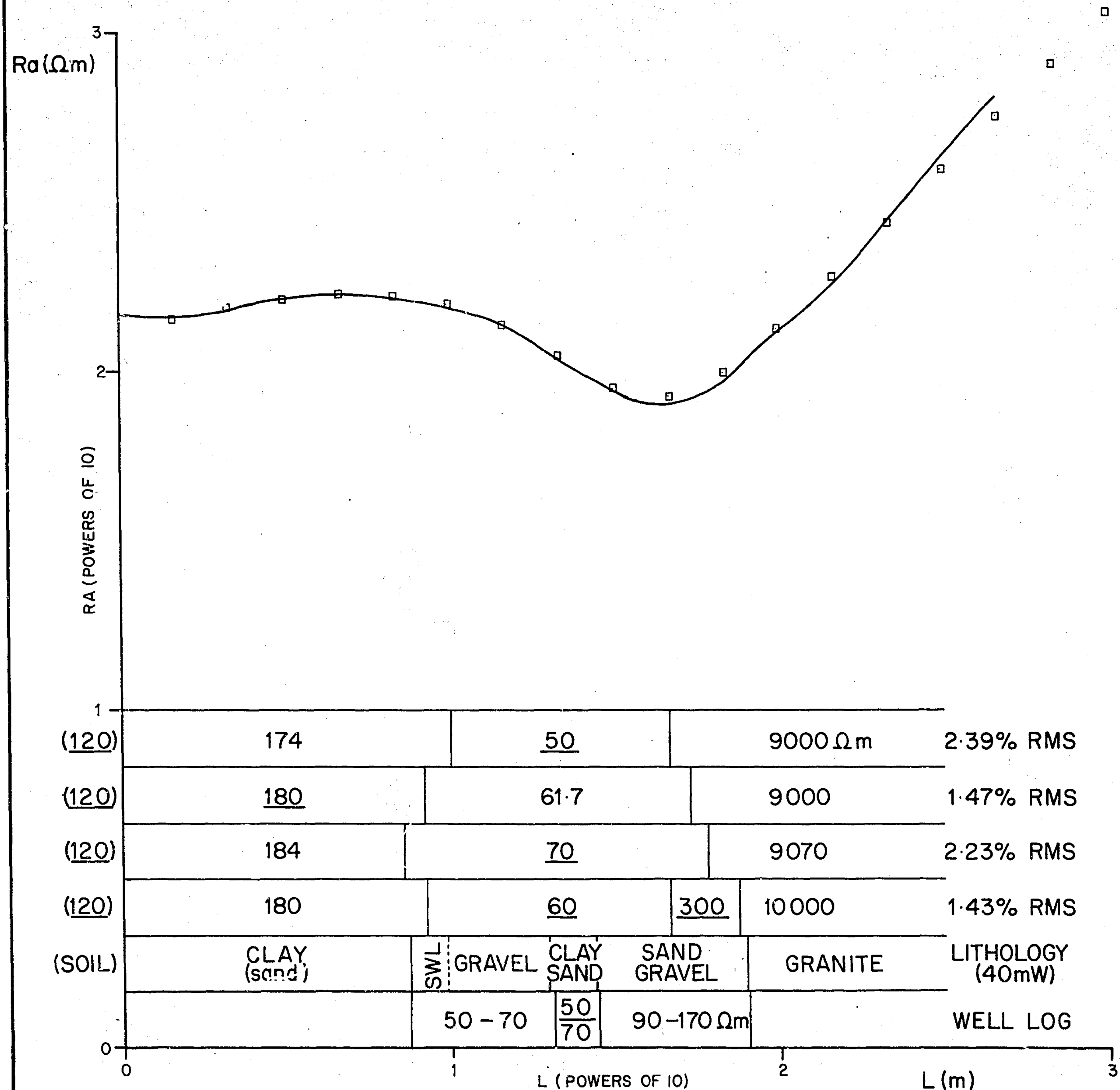

Ra(Ωm)
3
2
1
0
RA (POWERS OF 10)
(490) | 87·0 | ·5 | 53·0 | 850 Ωm | 1·79% RMS
(490) | 87·2 | 10 | 53·4 | 850 | 2·03% RMS
(490) | 87·0 | 15 | 53·0 | 850 | 3·55% RMS
(490) | 88·8 | 20 | 54·4 | 850 | 5·53% RMS
(SOIL) | SILT | CLAY | SWL | GRAVEL | SILT | SAND GRAVEL | GRANITE | LITHOLOGY
0·5 | 1·9 | 5·5 km/s | REFRACTION
0
1
2
3
L (POWERS OF 10)
L(m)

Fig.20



Ra (Ωm)
3
2
1
0
RA (POWERS OF 10)
(120)
174
50
9000 Ωm
2·39% RMS
(120)
180
61·7
9000
1·47% RMS
(120)
184
70
9070
2·23% RMS
(120)
180
60
300
10 000
1·43% RMS
(SOIL)
CLAY (sand)
SWL
GRAVEL
CLAY SAND
SAND GRAVEL
GRANITE
LITHOLOGY (40mW)
50 – 70
50/70
90 –170 Ωm
WELL LOG
0
1
2
3
L (POWERS OF 10)
L (m)

Fig.21

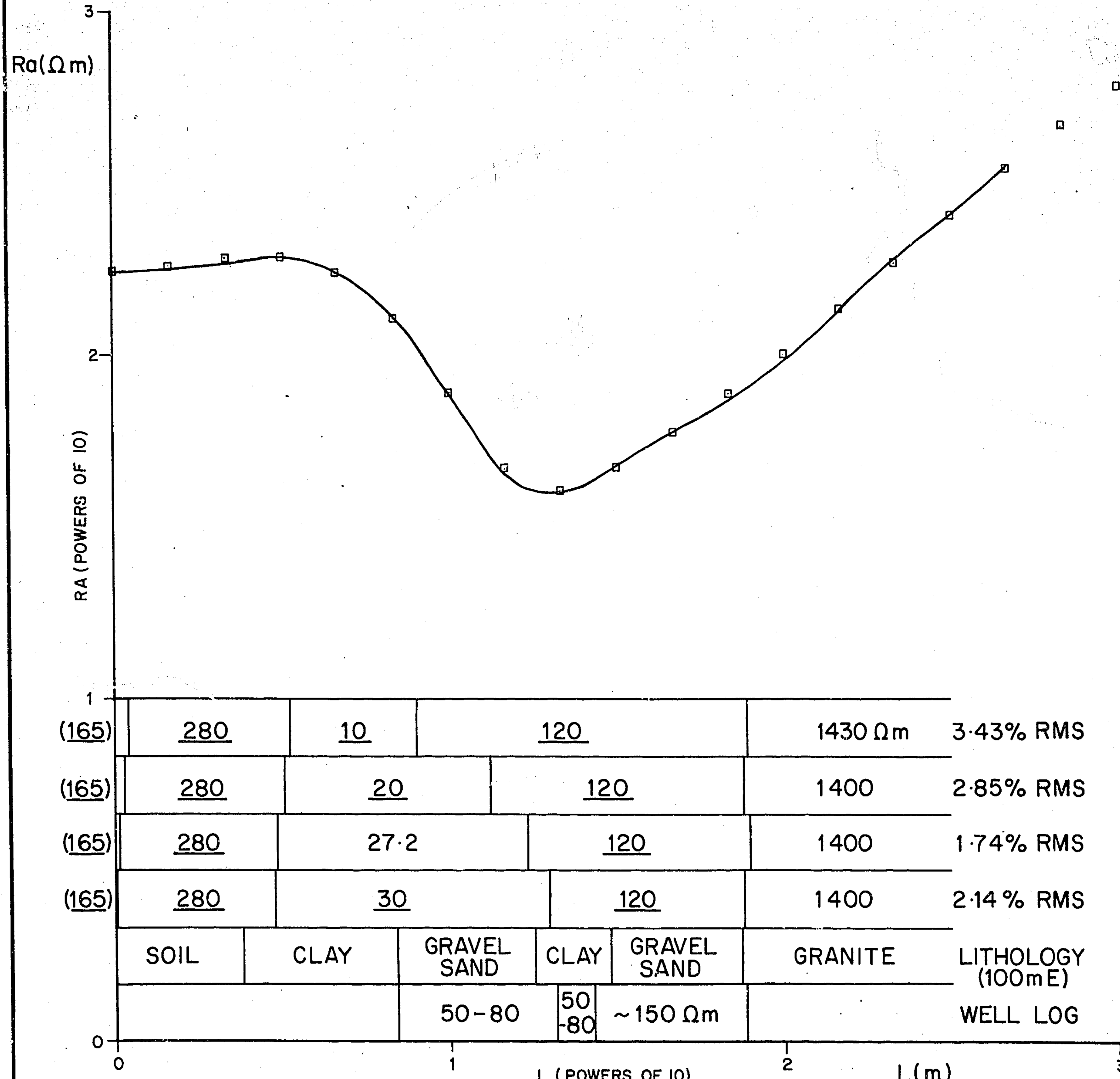
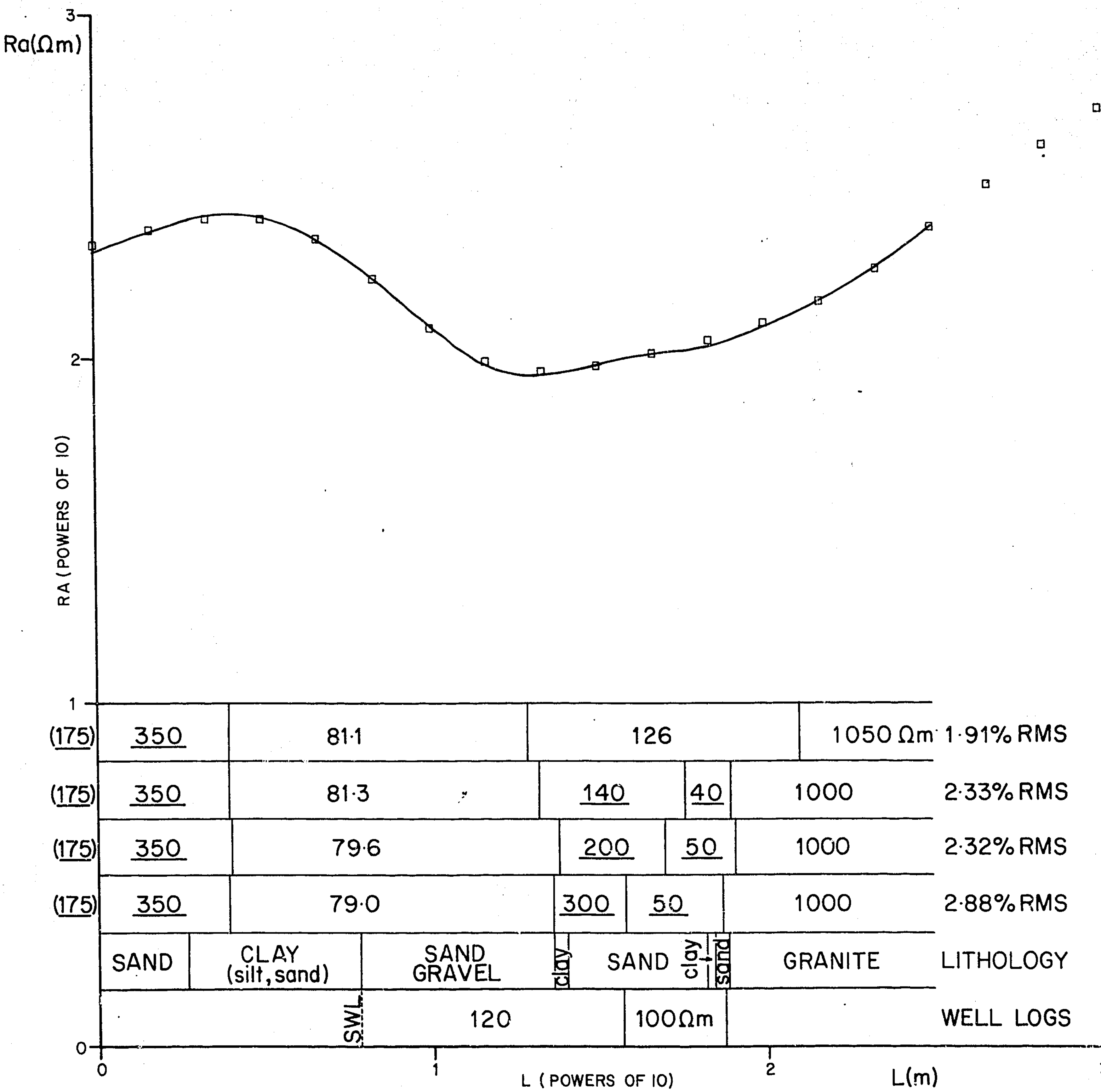
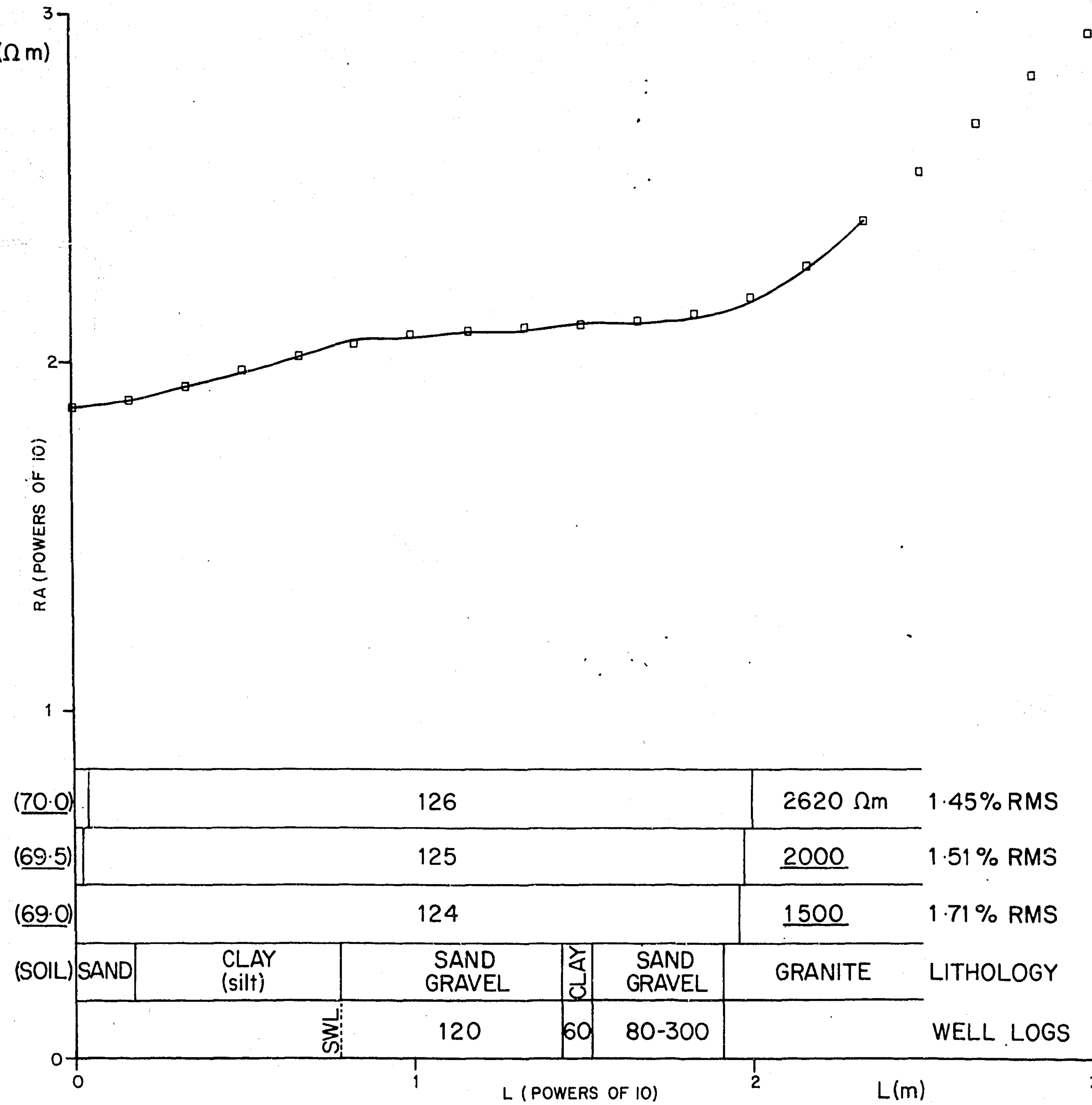

Ra(Ω m)
RA (POWERS OF 10)
3
2
1
0
(165)
280
10
120
1430 Ωm
3·43% RMS
(165)
280
20
120
1400
2·85% RMS
(165)
280
27·2
120
1400
1·74% RMS
(165)
280
30
120
1400
2·14 % RMS
SOIL
CLAY
GRAVEL SAND
CLAY
GRAVEL SAND
GRANITE
LITHOLOGY (100m E)
50-80
50 -80
~150 Ωm
WELL LOG
0
1
2
3
L (POWERS OF 10)
L(m)

Fig.22



Ra(Ωm)
RA (POWERS OF 10)
3
2
1
0
(175) 350 | 81·1 | 126 | 1050 Ωm | 1·91% RMS
(175) 350 | 81·3 | 140 | 40 | 1000 | 2·33% RMS
(175) 350 | 79·6 | 200 | 50 | 1000 | 2·32% RMS
(175) 350 | 79·0 | 300 | 50 | 1000 | 2·88% RMS
SAND | CLAY (silt, sand) | SAND GRAVEL | clay | SAND | clay | sand | GRANITE | LITHOLOGY
SWL | 120 | 100Ωm | WELL LOGS
0
1
2
3
L (POWERS OF 10)
L(m)

Fig.23



Record No.1976/108

Resistivity interpretation is hampered by ambiguity in layer thicknesses and in the correlation of layer resistivities with lithologies. Despite this, it is a very effective way of obtaining stratigraphic detail and it often provides good depth estimates to a number of boundaries. Its main limitations are equivalence, suppression, and lack of resistivity contrast.

In this paper I have attempted to show how to acquire more reliable data by the use of the Pole-Multidipole method. The interpretation of the data can then be made more credible by a method of automatic interpretation such as the one described here. Future advances in resistivity sounding will be in the direction of more realistic earth models for interpretation which will account for the wealth of information contained in field curve disturbances.

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Discussion on Mr N.P. Merrick's paper

D.E. Leaman (Tasmanian Dept of Mines)

How does your inversion program respond to large resistivity contrast and erroneous field data?

N.P. Merrick

The inversion programs handle erroneous data quite well by matching in a least squares sense. The initial limitation in inversion was the inability of published linear filter coefficients to handle large resistivity contrasts. Our inversion program was unable to work properly until we recalculated the filter coefficients satisfactorily; contrasts of 1000:1 are now acceptable.

R. Gerdes (SA Dept of Mines)

Have you tried the tri-potential method as proposed by Habberjam, Watson, and Carpenter for picking up small lateral inhomogeneities?

N.P. Merrick

I haven't tried the method. I am familiar with it, however, and it looks in principle to be a very good idea. I consider it to be the only justification for using the Wenner array. If you take three reciprocal measurements and apply procedures for removing lateral effects then you should get more reliable data.

R. Gerdes (SA Dept of Mines)

Do you think your method could use the same principle to resolve small clay interfaces?

N.P. Merrick

It would be hard to say. It's an approach we couldn't try at present under our existing field system because we have a d.c. system and use a mixture of brass stakes and porous pots for electrodes. In principle, reciprocal measurements and corrections for lateral effects can be applied to any electrode array, but I consider it more convenient, in the field, to use a.c.

Comment from the floor, speaker unidentified

We actually tried an electrode array similar to your PMD array with an a.c. system to overcome surface contact problems; one of the things we found in our experience was that if you are using an a.c. system you can run into coupling problems by having an electrode "outside the spread". This gives a lot of errors.

Mr Crawford (Darling Downs College of Advanced Education)

I wonder if any practising resistivity people here have tried using resistivity to solve the problems I am faced with in my work. I am toying with the idea of using resistivity. We have an irrigation area in which the water-table has dropped and is continuing to drop, and I am thinking of inserting a fixed electrode array on the surface to see if I can measure the penetration of irrigation water during irrigation as a means of defining whether the irrigation water goes to the water-table. Could it be possible to pick up dynamic changes in saturation of the soil and weathered rock and to measure advancing water fronts moving down to water-table?

<u>N.P. Merrick</u>

I think you could quite reliably measure differences in medium resistivity as times goes on, but whether you can interpret those absolute resistivities in terms of absolute saturation is another thing of course. There would probably be no realistic electrical boundaries to pick up apart from those that already exist. I think you would have to rely on the variation in absolute resistivity. I am sure you will get that, whether you can get anything quantitative out of it I do not know. You can get, however, qualitative information. Anyone else care to comment on that problem?

<u>D.E. Leaman (Tasmanian Dept of Mines)</u>

We have experimented, we have only a small electrode set up, it depends of course what your electrical resistivity contrasts are. We are just working in a pure sandy area. I think it is a matter of trying it and seeing what you get.

<u>J. Odins (NSW Water Conservation & Irrigation Commission)</u>

I think if we want to control this sort of thing, the problem is going to be to be able to predict the movement of water. We can perhaps predict the curves from the properties measured in the soil, but this means disturbing the soil. We may have to insert electrode arrays to the depths to which we think the disturbance will go.

<u>G. Pilkington (SA Dept of Mines)</u>

The Schlumberger system is a symmetrical electrode system whereas your electrode system is not. For a reasonable 'dip' the Schlumberger curve conforms to a normal horizontal layer curve; however, with the PMD system you could get lateral dip effects. Do you carry out a sounding with the remote electrode on the other side of the spread as well?

N.P. Merrick

Routinely, we haven't. The effects of dip are more pronounced with the PMD method. The Schlumberger method does seem to cancel the effects by having symmetrically placed current electrodes. One advantage with the PMD method in this regard is that we could do our traverse soundings simultaneously. With the Schlumberger you do one sounding, then come back and do a second sounding at right angles to the first; with the PMD method you can have a remote electrode to the north and to the south and switch alternately. We have not tried this yet, but the principle is there.

J. Odins (NSW Water Conservation & Irrigation Commission)

I think that if you do a line of soundings then any dip effects will be evident at various stages and perhaps could be quantitatively allowed for in the interpretation, whereas with the single sounding you have to know the dip to be able to interpret.

D. Woolley (NSW Water Conservation & Irrigation Commission)

One of the points about this is that in our interpretations in most surveys in NSW the dip is not generally a problem.

G. Pilkington (SA Dept of Mines)

In my initial question about dip I was commenting on areas such as hill-slopes where we have overburden etc.

N.P. Merrick

I feel that there is not much point in worrying about features like that until we know how to interpret them, and at the moment we cannot do that.

R. Gerdes (SA Dept of Mines)

In the computer programs you listed is it possible to modify the one on inversion for multiple dipping layers?

N.P. Merrick

If that model was definable quantitatively you could in fact build an inversion program around it. The inversion process will work for any method provided that the assumed earth model can be formulated to give predicted values and derivatives of the relevant geophysical property. For example, in magnetics or gravity if you have a model and you can take a derivative with respect to all models parameters, then the same inversion process will work. We have tried magnetic inversion for a fault model to get a feeling for whether inversion in this application would work. We found that the basic program gives quite a general inversion process. But multiple dipping layer theory for resistivity isn't there at the moment, to the best of my knowledge.

D.E. Leaman (Tasmanian Dept of Mines)

First of all I take it that most of your experience is in level ground, so therefore you would not have experience with the problem of having your remote electrode over the hillside. Topographic variation could be a problem, or there is the problem of basement variations especially in a resistive basement as you were talking about, where it is not unusual to have so-called basements both weathered and fresh. So you could have extensive weathering with very large tor-like bodies at depth and end up with a resistive basement which has very high relief, whereas the true basement may have very low relief. Now this must make a lot of difference to where the interpretation puts the actual basement, and you mentioned that there are complications regarding that. Therefore I would like to know whether the interpretation you showed in those interpreted profiles came before or after you examined the borehole data, because if you go into an area first off then I think using your method you could produce quite reliable results - more reliable than any other method - and which, if they show a bump or distortion, then using your methods you may possibly interpret that bump. But the question I am asking is, is it all necessary, because rapid changes can occur laterally in an area, the basement may show relief, the aquifer can change, and again I stress is all this detailed interpretation really necessary? Initially you can still use families of curves or look at the curve and get an idea of the variation of resistivity with depth. This is the older form of interpretation of resistivity data and where you correlate from one sounding curve to the next. On one of the examples you showed where you had 7 or 8 soundings in a line. I was hoping you would perhaps point out or emphasise more the change in character of the curves. Now a lot of information on lateral change can come out by just looking at the curves; also the electrical differences as you pointed out need not be the geological differences or the geological boundaries that you are seeking for a whole stack of reasons; this is why I made my comment about the water-table in an unconfined situation in unconsolidated sediments. The water-table should be observable unless there is something funny about the water-table or the salinity of the water, or the lithology that the water is in. The third thing that I wish to deal with is the problem of anisotropy, which we deal with quite extensively. I just wonder how much the interpretation is going to be affected if the electrode array is turned through 90 degrees. In the case of anisotropy in the ground, what is the effect of rotating your array with respect to the strike of the structure? The other thing that I would like to mention is in the first example that you gave. I was encouraged by the fact that you showed also the refraction data; I thought that was perhaps a bit more informative than the resistivity data.

N.P. Merrick

In the first case (Fig. 19) as you mentioned, I did not have well log control so I used seismic control; unfortunately the seismic bedrock depth estimate was well out; usually it is much better than that; relative to seismic, the resistivity method does not give depth information as accurately but it gives you much more stratigraphic detail, many more layers. We are normally working with 6 electrical zones; with seismic you will find 3 or 4 velocity zones, so that there is more detailed information in the resistivity curves. On the problem of anisotropy, when we go into a new area we always carry out cross-soundings initially and in most valley situations that we have encountered there has been very little effect. If we find that there is little anisotropic effect on that first sounding then we normally make the assumption that the others will not be affected unduly unless there is an obvious major change in the locality. As for your comment on quantitative interpretation, I guess that boils down to the philosophy of whether you should interpret anything quantitatively. If you do leave the interpretation at a qualitative level, however, I feel you are not obtaining all the information which the data can give you. Certainly a qualitative interpretation is often sufficient and quantitative depths may not always be warranted. But my direction of thought has been that, if you can interpret something quantitatively, then that leads the way to bigger things, perhaps getting something out of the absolute resistivities in terms of geology, but that door is completely shut until we break through the barrier of quantitative interpretation.

J. Odins, (NSW Water Conservation & Irrigation Commission)

Just a comment on this method of interpretation we are using at WCIC. This method developed logically. We found that in trying to use published type-curves to get an interpretation, the range of type-curves for natural resistivity contrasts was insufficient; we then initially looked into means of publishing our own curves but as three- and four-layer cases were inadequate for most field situation we said "why not model multi-layer cases?". This obviously led to trying inversion so it was purely from dissatisfaction with the range of curves available and their applicability for interpretation that we went ahead with this procedure.

N.P. Merrick

I think the next step in resistivity interpretation would be in finite element modelling. This should account for all the small features on curves, and if it could be done efficiently it could give quite a good geoelectric section with some geological meaning.

CASE HISTORY - WEST CANNING BASIN, WESTERN AUSTRALIA

D.L. ROWSTON

Geological Survey of Western Australia

(ABSTRACT ONLY)

The results of the geophysical phase of an integrated hydrological investigation of the westernmost part of the Canning Basin in Western Australia were outlined. The regional survey involved 91 seismic refraction and resistivity depth probes arranged in a fairly regular grid over an area of some 6000

km^2. Exploratory drilling and geophysical well-logging have since provided confirmation that the interpretation of the corresponding refraction probes has an accuracy of better than ten percent for the 17 bores completed.

Whilst the seismic refraction method proved most effective in determining the thickness of sediments overlying Archaean metamorphic and granitic bedrock, it could not differentiate individual layers within the sequence. There was obviously no significant contrast in the velocities of aquifer and aquiclude. A velocity inversion problem was encountered in coastal areas where high-velocity calcarenite occured at the surface. Sedimentary thicknesses up to greater than 590 m were indicated in refraction spreads up to 1.6 km long.

The outcome of the Schlumberger electrical soundings with AB/2 up to 500 m was disappointing in that curve interpretations were rarely compatible with either seismic or drilling information. Normal resistivity well-logs indicated that the resistivity contrast between aquiclude (20 ohm-m) and aquifers (100 ohm-m) was adequate and that layer thicknesses at 50 m or better should have been detectable. Even the depth to highly resistive bedrock was interpreted with acceptable accuracy in only a few instances.

Despite these shortcomings the geophysical work, and particularly the seismic technique, provided a clear picture of the basin structure and total thickness of sediments. Well-logging clearly indicated the aquifers and permitted realistic evaluations of the qualities of the groundwater contained therein. Seismic velocities in the sediments could be equated with saturated or dry material and otherwise, the degree of consolidation and cementation of the strata.

DISCUSSION FOLLOWING D.L. ROWSTON'S TALK.

D.L. Rowston

I think that the survey that I have just described was very largely successful; drilling has seemed to confirm our results. I am very surprised, and you probably are, that the resistivity method did not solve some problems. The resistivity contrast indicated by the resistivity well-logs, between the two aquifers and a thick aquiclude which was about 50 metres thick and quite persistent over the whole area was adequate for detection. The resistivity indicated by the logs for the aquiclude was about 20 ohm-metres, and the aquifer around 100 ohm-metres, so there is a very good contrast. I am just wondering why the resistivity method cannot indicate such good layering. You have a thick sand, a thick aquiclude, another thick aquifer, and then infinitely resistive basement. The field data was generally good; we used a McPhar R204 equipment with an 800-volt input, currents up to about 2 amps.

N.P. Merrick (NSW Water Conservation & Irrigation Commission)

What sort of voltage signals were you receiving? The order of millivolts?

D.L. Rowston

I can't recall at this moment as the survey was over two years ago. Extremely low voltages, if my memory serves me correctly (lower limit about 0.2 millivolts).

N.P. Merrick (NSW Water Conservation & Irrigation Commission)

The conductive surface layer may contribute to the problem.

D.L. Rowston

Yes, I can understand that we are not getting below the masking effect of the conductive surface clays. However, in the areas away from the coast there were good surface clay contacts, good currents being transmitted, and good voltages received. I consider the field data to be quite reliable. The field method produced 3 depth probes per day, normal Schlumberger, AB/2 equals 500 metres maximum. There was some displacement between the branches of the Schlumberger curve for different MN values, particularly in areas where we couldn't get good contacts, such as some desert areas. Of the 35 or so depth probes we carried out, only 5 tallied very well with the seismic and/or drilling results as far as depth to bedrock goes. The layering above the bedrock as interpreted by resistivity, showed no coincidence with the drilling.

N.P. Merrick, (NSW Water Conservation & Irrigation Commission)

Are the resistivities constant over the area?

D.L. Rowston

Yes they are constant except towards the western part of the area, where the groundwater salinities increase. This is where the resistivity curves show very little character. However, in the central area the curves should have exhibited far more character but didn't. The ground is saturated in this area too. I cannot understand this and I would welcome any suggestions, both for this problem and also the problem of detecting layering in this area by the seismic refraction method.

J.Odins (NSW Water Conservation & Irrigation Commission)

How do you know that there is a velocity inversion?

D.L. Rowston

What else could it be?

J. Odins

Perhaps it is a blind zone problem.

D.L. Rowston

It perhaps could be a blind zone problem but I am looking at this problem in retrospect from the drilling results. The sediments appear to be quite unconsolidated except for cemented layers at the surface, i.e. normal poorly cemented friable sandstones and saturated.

J. Odins

So you then have no velocity information on the underlying sediments.

D.L. Rowston

No, occasionally where the high-velocity surface layer peters out we can insert a velocity from adjacent spreads. This introduces a small error.

However, as this is a regional study I have not considered this to be terribly important. The drilling is still in progress and the survey results will be re-examined fully when it is completed.

J. Odins

There is a new recording paper out by Kodak; the image is much more permanent and it is suitable for Xeroxing and copying. I think the number is Kodak 1895. I am not sure.

D.L. Rowston

We have been using Agfa film and just recently obtained some new Kodak paper; I will check on the availability of the new paper you mention. It is a very risky business using dry-write paper in the north of Australia where there is so much sunlight in field working conditions. The recorder is operated from the back of a Landrover and one has to be careful not to let too much direct sunlight in. The fixer that often comes with these papers doesn't seem to be very good either. The developing process seems to be continuous once it is exposed to daylight.

R. Gerdes (SA Dept of Mines)

You have a magnetic basement in the area; have you tried using magnetic basement contours?

D.L. Rowston

Some of the metamorphics are magnetic, some are not. I should mention that we have the BMR Bouguer gravity of the area; there is a very large high of about 30 milligals on the western side which we know for sure is over metamorphics. Quite a few of the Archaean granites are relatively light - they have densities of about 2.62 compared with perhaps 2.8 grams per cc for metamorphics. This high may indicate a fairly deep seated feature, but what it does indicate is that in the western area there is a clear relation of gravity highs to metamorphics. However,,in answer to your question we do not have any aeromagnetic data. The BMR have flown a couple of lines in the vicinity but they traverse from Goldsworthy to Broome and miss out the area we are investigating. The Bureau have already worked out basement depths on these lines, I think that was how they originally defined the Wallal(?) Platform, in conjunction with gravity evidence. The BMR Wallal Bores are on the coast, where the basement depths are of the order of 680 metres; the geophysical results show further along the line a small trough, and our area appears to be on the edge of that trough. If there had been aeromagnetics of the area we would have used them.

Mr Crawford (Darling Downs College of Advanced Education)

Did you make use of these bores further south of the area; did you get any high gamma anomalies in these bores?

D.L. Rowston

No high gamma anomalies were noticed. There does not seem to be any uranium in the calcretes although these calcretes are often quite extensive and therefore largely untested.

SEISMIC INVESTIGATION OF HYDROGEOLOGICAL PROBLEMS

B.E. MILTON & R.G. NELSON

South Australian Department of Mines

ABSTRACT

Seismic velocities of rock are related mainly to the properties of density, porosity, and the various elastic moduli. Contrast between these properties in succeeding strata of rocks yield seismic discontinuities. By locating these discontinuities, associated geological horizons may be mapped.

In loose unconsolidated sediments, seismic velocity depends on depth of burial, type of packing, and degree of water saturation. When dry or only partly saturated these sediments commonly have low velocities (500 m/s or less), but with nearly complete saturation the compressional velocity approaches that of water (about 1500 m/s). Thus, the seismic method can be used to locate the depth to water in the case where a free water-table exists. However, in fine sands and silts, especially where organic matter and gases are present, measured velocities may be anomalously low.

Correlation with other methods can often give results which are more indicative of the presence or absence of water. Such methods include the measurement of shear wave velocities and of electrical resistivities. The use of gravity methods in conjunction with seismic work can lead to estimates in the variation of bulk densities with depth. Surveys which involve several methods are strongly recommended.

Case histories from a variety of geological environments in South Australia are used to illustrate these ideas.

A. Aims

The aims of the seismic method as applied to groundwater investigation are twofold:

1. to determine the depths to discontinuites within the sedimentary section of basins, etc. and/or between sediments and bedrock, and so plot these surfaces;
2. to measure seismic velocities and use them in the prediction of rock types, porosities, and depth to water-table.

B. Principles and theory

An acoustic signal is introduced into the ground, e.g. by exploding a charge of dynamite. A recording system is then used to measure the times at which the seismic waves thus generated arrive at a spatial array of detectors, generally set out on the surface of the ground. Most commonly detectors are arranged in line with the energy source and at right angles to geological strike. With this type of array the information recorded can be interpreted so as to give a two-dimensional section of seismic horizons.

The method depends on the contrast between the elastic properties of succeeding strata of rocks. In most cases seismic discontinuities coincide with geological horizons. From the data recorded the depth to and dip of the discontinuities may be calculated.

Analysis of seismic data is based on the methods of geometrical optics. Wave travel-paths are treated as ray paths, and mathematical expressions derived from geometrical models are used. Figure 1 shows the types of events which can be recorded. Of these, reflection events are of prime importance in investigating deep sedimentary phenomena; refraction events are more useful in shallow conditions. Ray paths are generally assumed to be linear, as in the case where the velocity within a layer remains constant throughout the layer.

Seismic velocities are related to density and porosity, amongst other rock properties. Hence, these characteristics and changes in them can be predicted to some degree. Figure 2 shows major categories for seismic velocities for different rock types. Note that dry unconsolidated sediments often have compressional velocities lower than that of water. The effect of water saturation on compressional velocity through a packing of quartz spheres as a function of depth and type of packing is shown in Figure 3 (after Emerson, 1968). It is noteworthy that the effect of partial water saturation on a dry sphere pack is insignificant until nearly complete water saturation is achieved.

Mostly interpretation is based on measurements of the compressional-wave velocity Vp. However, if the slower shear-wave velocity, Vs, can be measured as well, then the various dynamic elastic moduli of the rock concerned can be calculated, provided its density is known (Fig. 4). The ratio Vp:Vs may be of importance in distinguishing water-saturated sediments from rocks having similar compressional velocities (Fig. 5, after Paterson and Meidav, 1965).

Another aid in identifying rock type is the electrical resistivity, which decreases with increasing porosity, degree of saturation, and salinity of the saturating liquid. Figure 6 gives a broad generalisation of the relation between rock type, seismic velocity, and electrical resistivity.

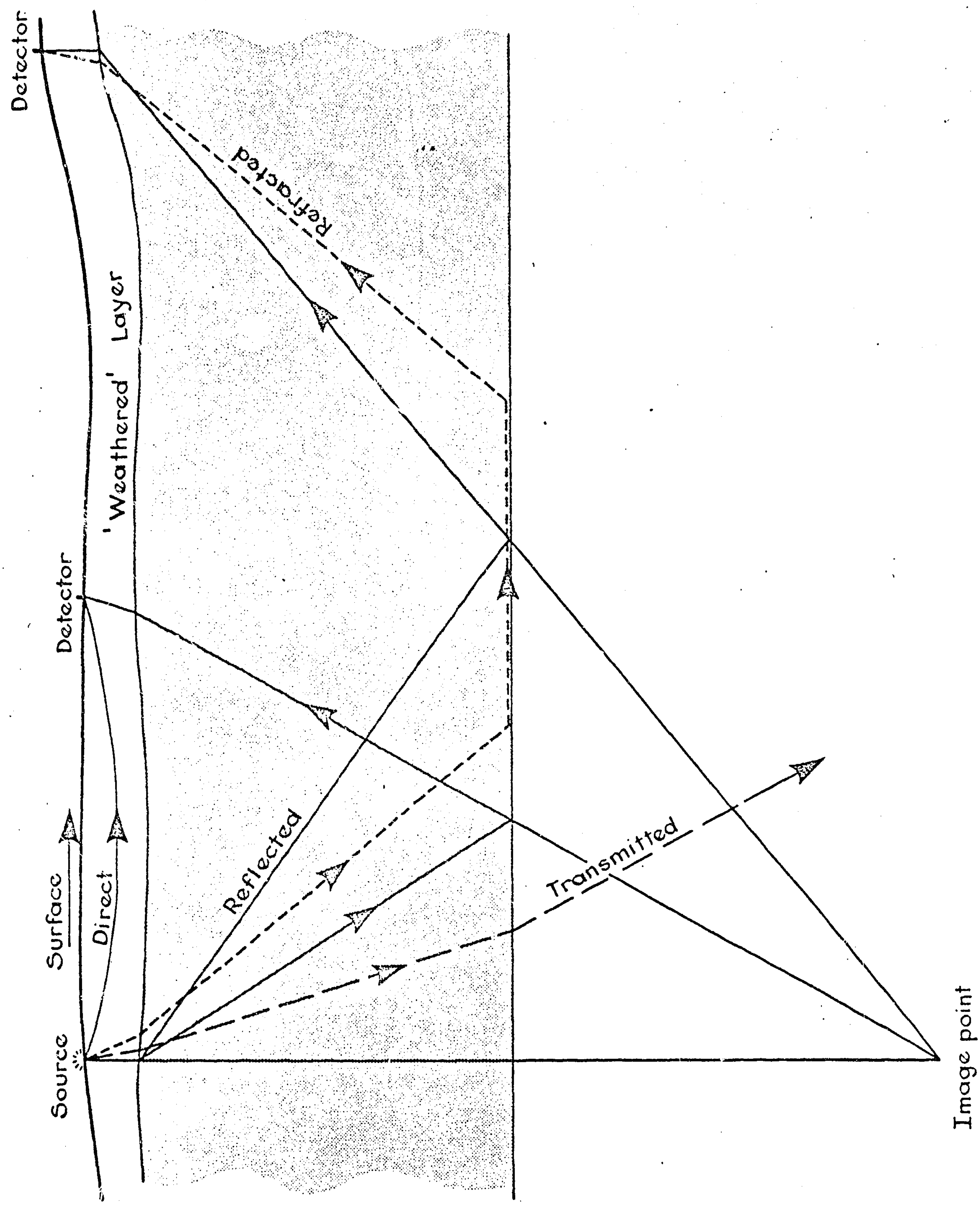


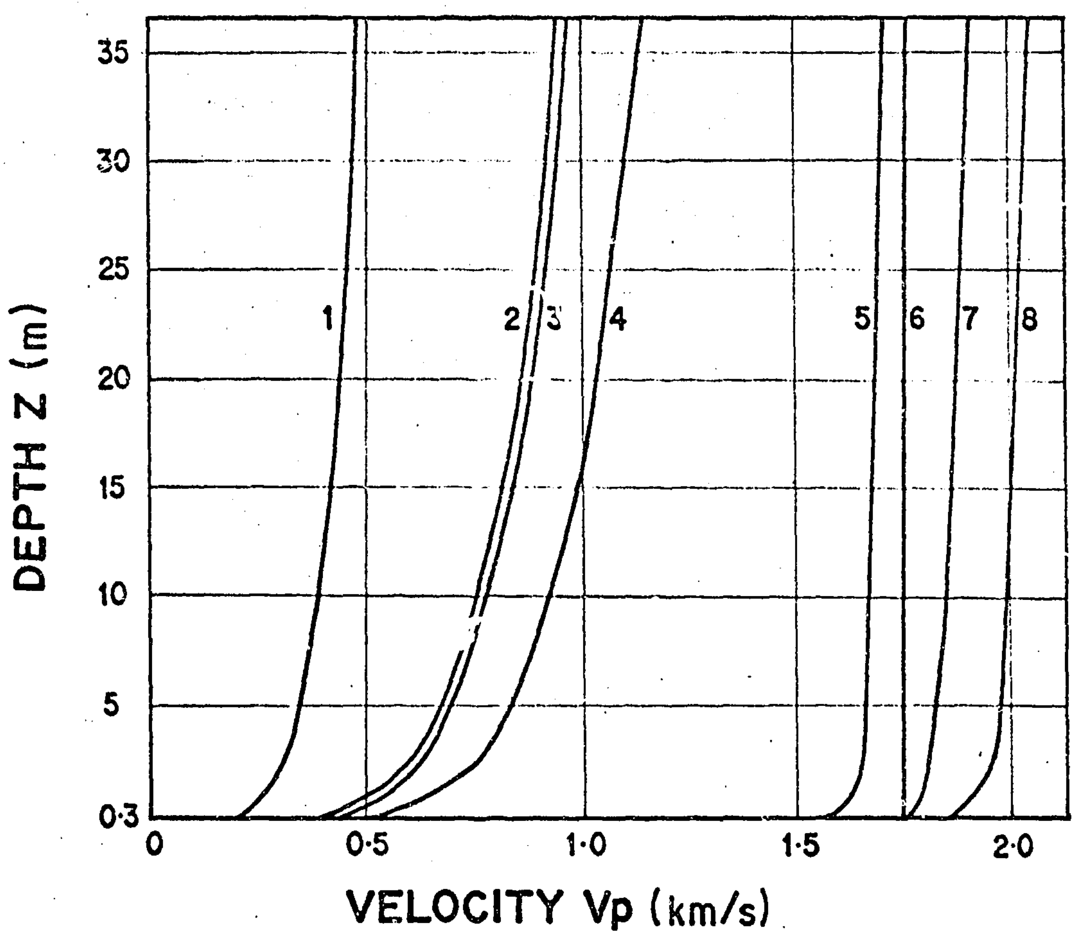
FIG.1

	DEPARTMENT OF MINES – SOUTH AUSTRALIA	SCALE
COMPILED: R G N	GEOPHYSICAL METHODS IN HYDROGEOLOGY POSSIBLE WAVE PATHS	DATE: OCTOBER '76
DRN. L C / CKD.		PLAN NUMBER S12417
GEOPHYSICAL SERVICES		

	MEDIUM	VELOCITY
1.	Air.	330 m/s
2.	Water.	1450 m/s
3a.	Alluvium, soil (relatively unconsolidated, recent) - dry.	150 - 1000 m/s
3b.	Alluvium, soil (relatively unconsolidated, recent) - water saturated.	1400 - 1800 m/s
4.	Sandstones & shales.	1800 - 4200 m/s
5.	Limestones, dolomites & related calcareous deposits.	2100 - 6100 m/s
6.	Granites & other crystalline igneous rocks.	4600 - 5800 m/s
7.	Metamorphic rocks.	3000 - 7000 m/s

FIG.2

	DEPARTMENT OF MINES - SOUTH AUSTRALIA	SCALE.
COMPILED: RGN	GEOPHYSICAL METHODS IN HYDROGEOLOGY	DATE: OCTOBER '76
DRN. LC / CKD.	MAJOR CATEGORIES FOR SEISMIC VELOCITIES	PLAN NUMBER: S12418
GEOPHYSICAL SERVICES		



CURVE	PACKING	PORE SATURANT	a(approx.)	x(approx.)
1	HEXAGONAL (HOR.)	AIR	270	0·17
2	CUBIC	AIR	522	0·17
3	HEXAGONAL (VERT.)	AIR	514	0·17
4	RHOMBOHEDRAL	AIR	643	0·17
5	CUBIC	WATER	1617	0·017
6	HEXAGONAL (HOR.)	WATER	1753	0
7	HEXAGONAL (VERT.)	WATER	1796	0·017
8	RHOMBOHEDRAL	WATER	1897	0·017

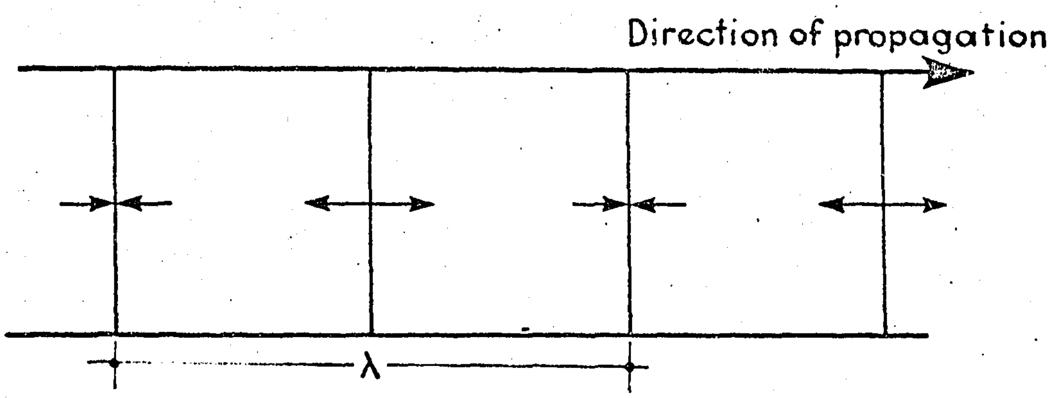
$$Vp = aZ^{x}$$

(after Emerson)

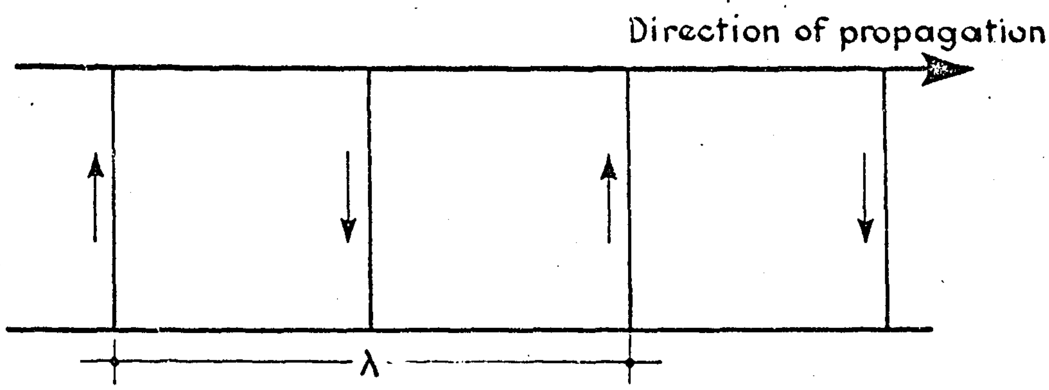
FIG. 3

	DEPARTMENT OF MINES – SOUTH AUSTRALIA	SCALE.
COMPILED: R.G.N.	GEOPHYSICAL METHODS IN HYDROGEOLOGY THEORETICAL COMPRESSIONAL WAVE VELOCITIES IN SPHERE PACKS	DATE: OCTOBER '76
DRN: L.C. CKD.		PLAN NUMBER:
GEOPHYSICAL SERVICES		S12432

COMPRESSIONAL WAVES

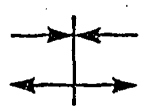


SHEAR WAVES



Direction of particle motion indicated by arrows

Compression
Dilatation



$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} = \sqrt{\frac{E}{\rho}\,\frac{1-\sigma}{(1-2\sigma)(1+\sigma)}} \qquad V_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{\rho}\,\frac{1}{2(1+\sigma)}}$$

K	bulk modulus
μ	shear modulus
ρ	density
E	Youngs modulus
σ	Poissons ratio

$$\frac{V_p}{V_s} = \sqrt{\frac{K}{\mu} + \frac{4}{3}} = \sqrt{\frac{1-\sigma}{\frac{1}{2}-\sigma}}$$

FIG.4

		DEPARTMENT OF MINES – SOUTH AUSTRALIA	SCALE.
COMPILED: R.G.N.		GEOPHYSICAL METHODS IN HYDROGEOLOGY RELATIONSHIPS BETWEEN COMPRESSIONAL AND SHEAR WAVE VELOCITIES	DATE OCTOBER '76
DRN: L.C.	CKD.		PLAN NUMBER
GEOPHYSICAL SERVICES			S12419

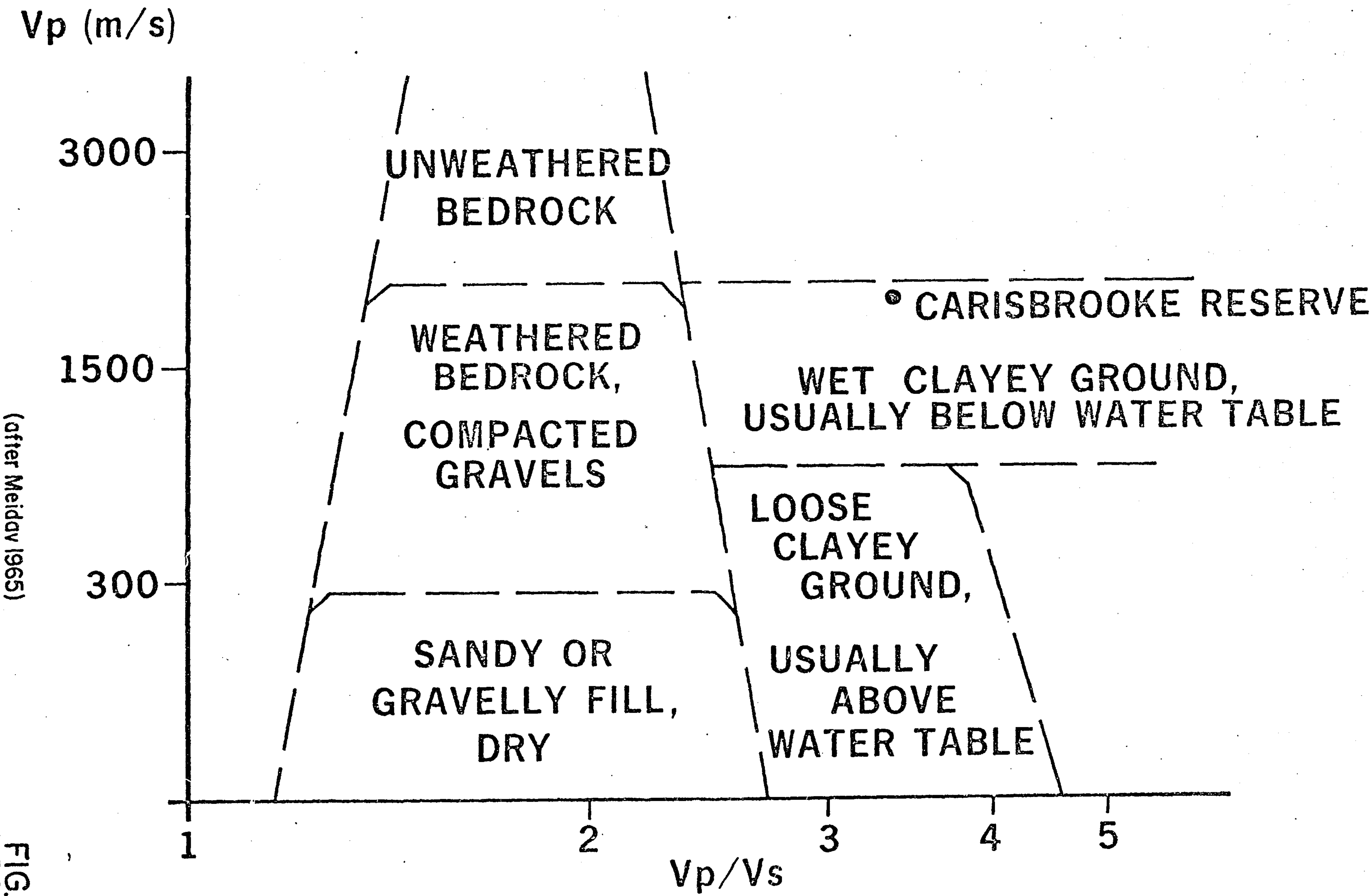


FIG.5

(after Meidav 1965)

DEPARTMENT OF MINES–SOUTH AUSTRALIA

GEOPHYSICAL METHODS IN HYDROGEOLOGY
LITHOLOGY AGAINST Vp and Vp/Vs

COMPILED: R.G.N.

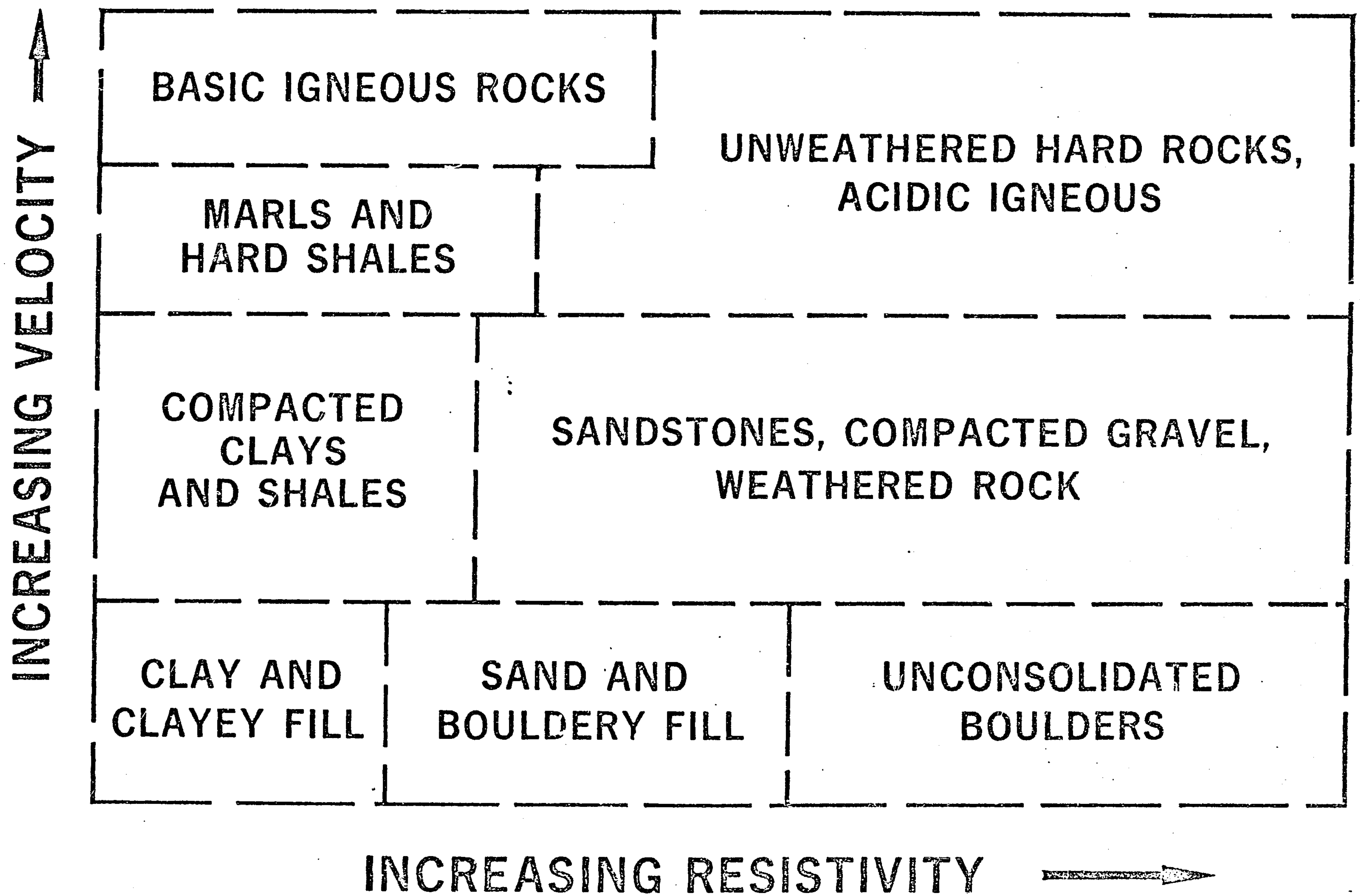
DRN | CKD

GEOPHYSICAL SERVICES

SCALE.

DATE: OCTOBER '76

PLAN NUMBER S12420



(after Paterson)

FIG.6

DEPARTMENT OF MINES—SOUTH AUSTRALIA

GEOPHYSICAL METHODS IN HYDROGEOLOGY
RELATIONSHIP BETWEEN ROCK TYPE,
RESISTIVITY & Vp

COMPILED: R.G.N
DRN.
CKD.
GEOPHYSICAL SERVICES

SCALE
DATE OCTOBER '76
PLAN NUMBER
S12421

C. Mathematical treatment

A full development of analytical methods of interpreting seismic data is beyond the scope of this paper. The interested reader is referred to standard text books on geophysics (e.g. Dobrin, 1960; Heiland, 1946; Griffiths & King, 1965). A broad outline of some of the techniques used is given below.

1. Reflection method (Fig. 7)

The time sections recorded from a detector array are processed to remove unwanted effects (e.g. multiple reflections between beds). These processed time sections can then be used to map reflectors associated with formations of interest in the subsurface geology.

Depth below a reference point is calculated using reflection times and the average velocity from the datum plane to the reflecting horizon. Velocity information is obtained preferably from wel logs or indirectly from seismic data.

2. Refraction method

This method is most appropriate to shallow investigations such as groundwater problems, where it is difficult to achieve the high signal resolution required to measure reflections.

Travel times are either:

(a) corrected for variations in elevation and irregular low-velocity layers near the surface and referred to a horizontal datum; or

(b) referred to the ground surface as datum.

(a) Times corrected to a horizontal datum.

Corrected arrival times for a series of in-line geophones are plotted against horizontal distance from the source. The "time-distance curve" fitted to the plotted points generally consist of one or more straight line segments (Figs. 8 and 9). The inverse of the slope of each line segment is the

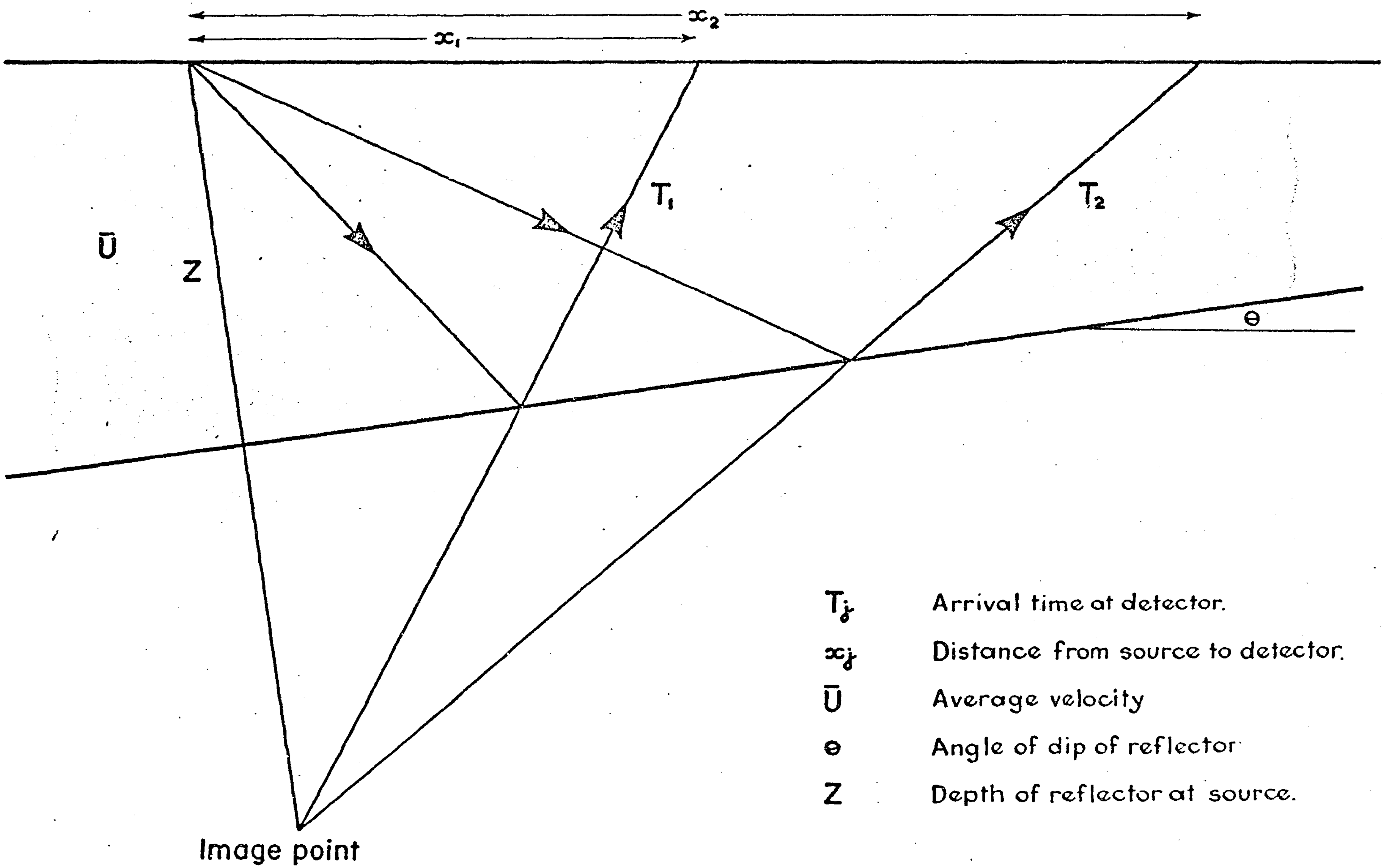


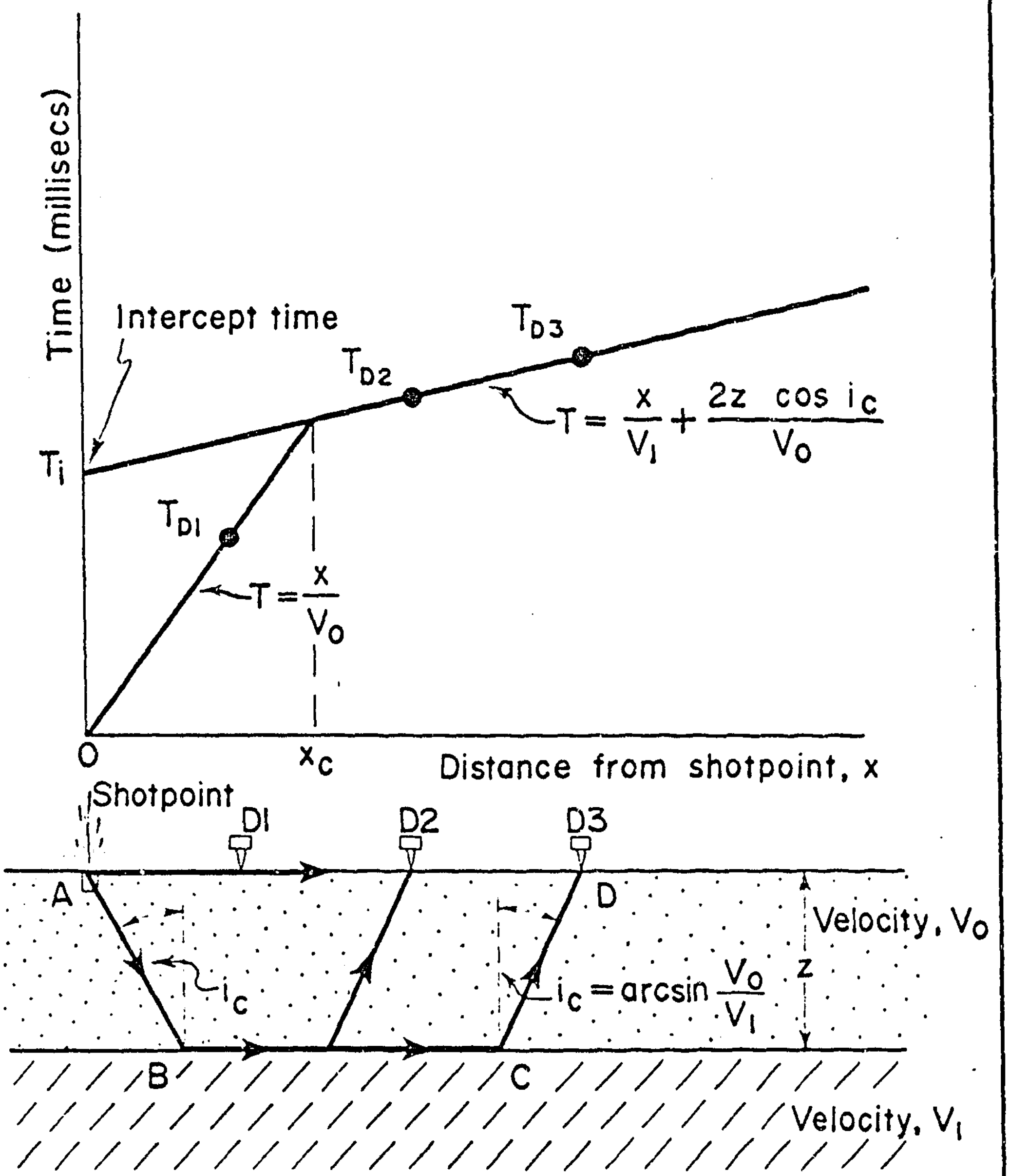
FIG. 7

DEPARTMENT OF MINES–SOUTH AUSTRALIA

GEOPHYSICAL METHODS IN HYDROGEOLOGY

REFLECTION RAY PATHS

COMPILED. R.G.N	
DRN. L.C	CKD.
GEOPHYSICAL SERVICES	
SCALE	
DATE. OCTOBER '76	
PLAN NUMBER. S12422	



Travel times

(a) Direct wave: $T = \frac{x}{V_0}$

(b) Refracted wave: $T = T_{AB} + T_{BC} + T_{CD}$

$$T_{AB} = T_{CD} = \frac{z}{V_0 \cos i_c}$$

$$T_{BC} = \frac{x - 2z \tan i_c}{V_1}$$

FIG. 8

DEPARTMENT OF MINES — SOUTH AUSTRALIA

GEOPHYSICAL SERVICES SECTION	Drn. R.N.	SEISMIC REFRACTION TWO LAYER CASE	SCALE:
	Tcd. A.F.		S11496
	Ckd.		
	Exd.		DATE: April 1975

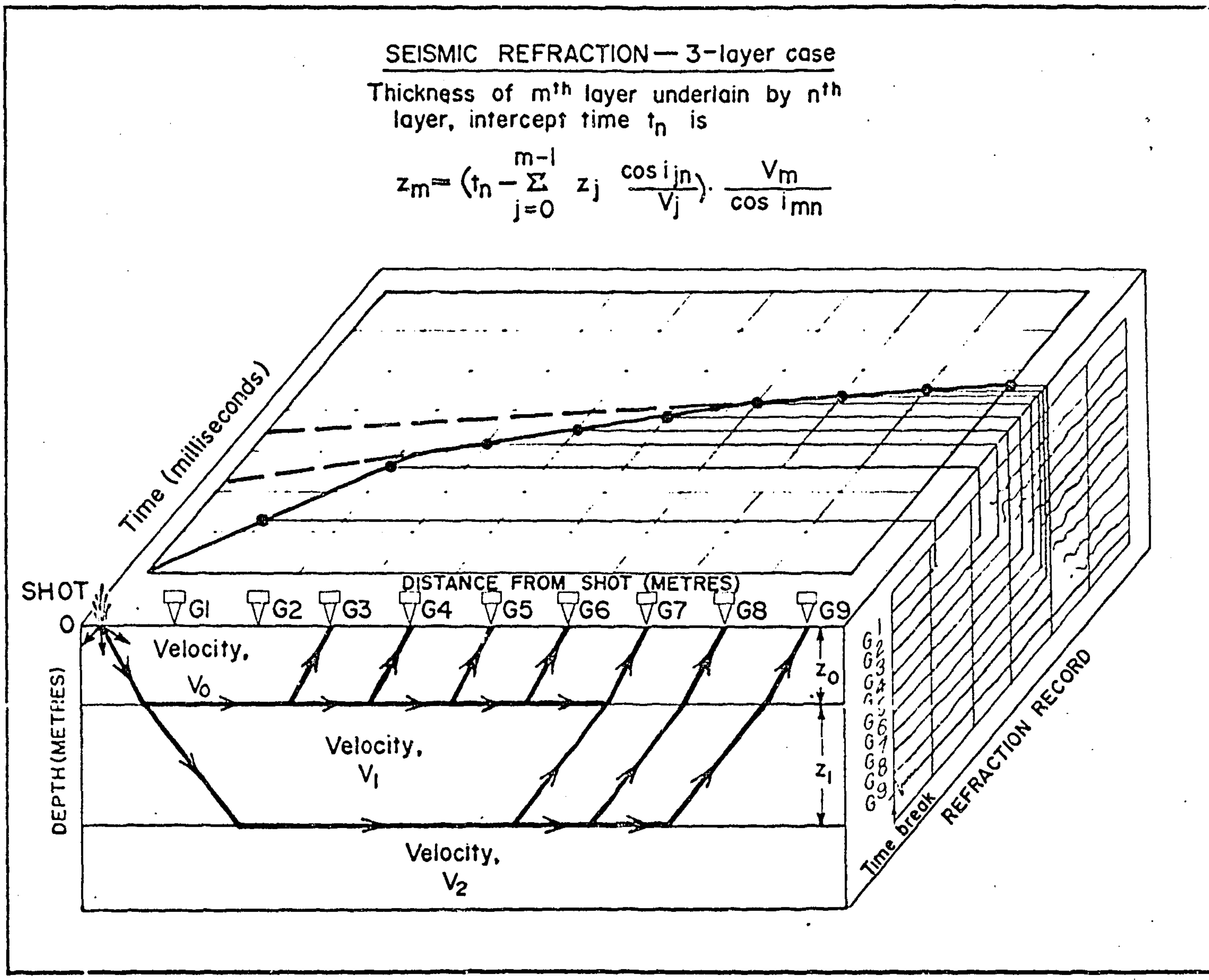


FIG. 9.

DEPARTMENT OF MINES — SOUTH AUSTRALIA

GEOPHYSICAL SERVICES SECTION	Drn. R.N	SEISMIC—REFRACTION MULTILAYER CASE	SCALE:
	Tcd. A.F.		S11497
	Ckd.		
	Exd.		DATE: April 1975

"apparent velocity" of the wave along the refraction interface, and this varies with the direction and amount of dip.

True velocities are found by combining results of "reciprocal shooting", i.e. detector spreads shot from each end.

The depth to the refractor can be calculated from certain features of the time-distance curve, e.g. the "critical distance", X_c, or the "intercept time" (Fig. 8).

From Snell's Law

$\sin (i \pm \theta) = Uo/Vu$ or Uo/Vd,

where

i = critical angle = arcsin Uo/V,

Uo = vertical average velocity of the material above the refractor,

V = true velocity of the refractor,

θ = angle of dip of the refractor,

Vu = apparent velocity shooting updip,

and Vd = apparent velocity shooting downdip.

One form of depth calculation using the intercept time Ti is

$$Z = Ti\ Uo/2 \cos \theta \cos i$$

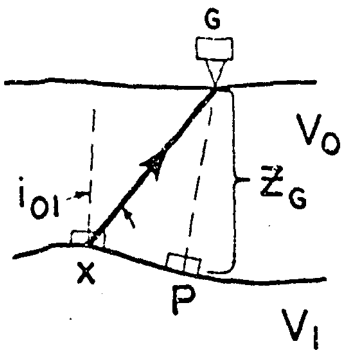
(b) Times referred to ground surface as datum.

For shallow problems, calculation of the depths below ground surface of refractors of interest can be made at each detector station. Hawkins (1961) gives details of a method in frequent use for analysing shallow refraction results (also Fig. 10, this paper).

D. Equipment

1. Energy source

Explosives are generally used in shallow work, either at the surface or in a shot-hole. For deep penetration, alternative energy sources are available, e.g. "Vibroseis". The shot instant is recorded on the seismic record, the pulse being transmitted by line or radio to the recording apparatus.

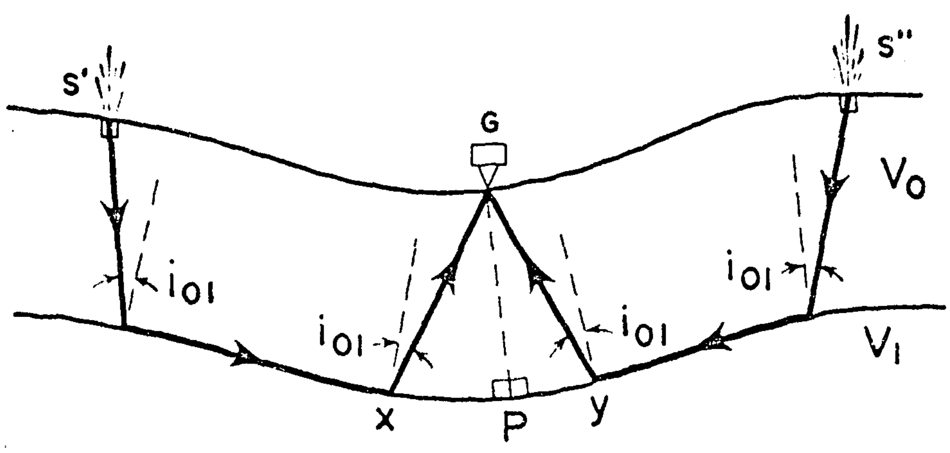


TIME DEPTH

T_G = time delay in travelling between refractor and surface

$$= \frac{Gx}{V_0} - \frac{Px}{V_1}$$

$$= \frac{Z_G \cos i_{01}}{V_0}$$



$$T_G = \tfrac{1}{2}(T_{S'G} + T_{S''G} - T_{S'S''})$$

(1) Determine reciprocal time $T_{S'S''}$

(2) Add recorded travel times from shooting each way

(3) Subtract $T_{S'S''}$ and divide by 2

(4) Calculate depth Z_G

FIG. 10

DEPARTMENT OF MINES — SOUTH AUSTRALIA

GEOPHYSICAL SERVICES SECTION	Drn. RN	SEISMIC REFRACTION	SCALE:
	Tcd. AF	METHOD OF RECIPROCAL ANALYSIS	S11495
	Ckd.		
	Exd.		DATE: April 1975

The advent of digital recording techniques, especially where signals can be stored and stacked in memory, has meant that repeated input signals from weaker energy sources can be used as an alternative to a single input signal from a large source.

2. Detecting units

Signals are detected by earth microphones capable of responding to earth movements of 10^{-6} to 10^{-7} mm. These geophones are designed with resonant frequencies appropriate to the type of energy anticipated, e.g.:

4.5 Hz for deep refractions,
7 Hz for shallow "
14 Hz for reflections.

3. Recording system

Signals from the detectors are fed to a system of amplifiers. Electronic processing can be applied to improve the signal-to-noise ratio. A permanent record is made on sensitive paper, and, for deep exploration, also on magnetic tape. Fiducial lines are printed at 10-millisecond intervals, so events can be timed to 1-millisecond accuracy.

E. Advantages and limitations

1. Advantages

The outstanding characteristic of the seismic method is the accuracy of determination of depths to elastic discontinuities, from which subsurface structure can be plotted. This applies to both broad-scale and small phenomena, such as buried water channels. In groundwater investigations, velocity information can be related to porosities and used to establish the depth to the water-table.

2. Limitations of refraction shooting

(a) Where velocities of sediments and underlying bedrock overlap, the method cannot locate the contact.

(b) An intermediate formation must have a minimum thickness dependent on relative velocities, before it can be detected as a first refraction arrival.

(c) For a multilayer case, the velocity of each layer must be greater than that of the shallower layers for refractions to be recorded.

(d) Field equipment is relatively complex and costly. The use of explosives can be difficult in some areas. The amount of space required to lay out refraction spreads can be a limiting factor.

3. Limitations of reflection shooting

For reflection profiling, conversion of times to depths depends on a knowledge of the velocity/time relation.

F. Case histories

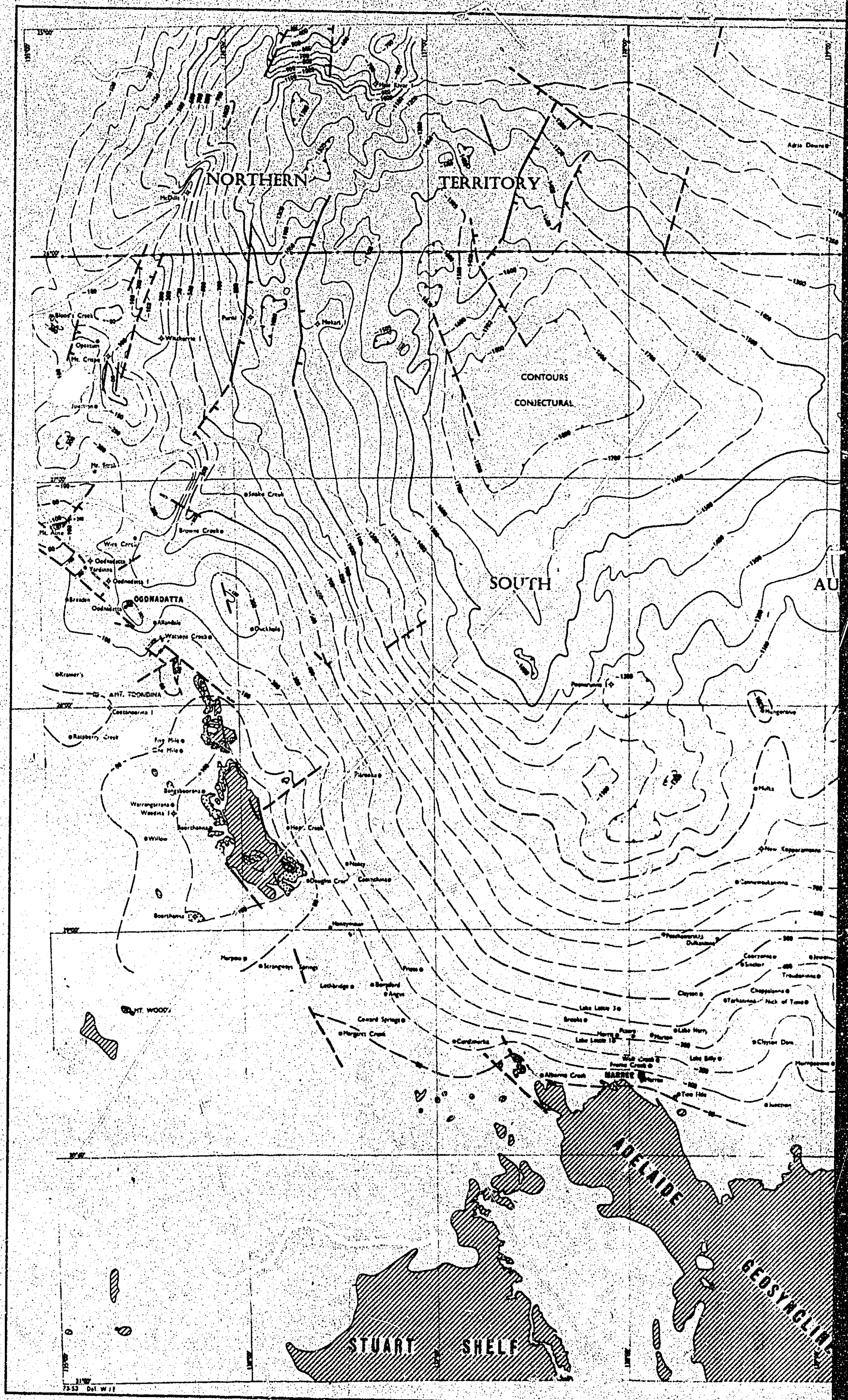
1. Reflection methods

(a) Deep aquifers - western Great Artesian Basin

The main aquifer of the Great Artesian Basin, the Algebuckina Sandstone, has been mapped accurately by reflection profiling. The actual reflecting horizon is the Cadna-Owie Formation, which overlies the aquifer. Early work in the western part of the basin enabled the "C" reflector to be plotted over large areas and velocity/time and depth/time functions to be calculated with good reliability from the seismic data.

The Cadna-Owie Formation was cut in the Birdsville town bore in April 1961, at 1076 m below MSL. The depth calculated from prior seismic work 1.5 km away was 1146 m, which gave 1112 m at the well site when corrections for regional dip were applied. The C horizon can now be plotted over much of the basin to an accuracy of a few metres.

The structure contour plan (see Fig. 11) demonstrates the power of the reflection method to plot subsurface geology in terms of depth and structure and its application to the investigation of a deep aquifer.


NORTHERN
TERRITORY
CONTOURS
CONJECTURAL
SOUTH
OODNADATTA
ADELAIDE
STUART
SHELF

(56)

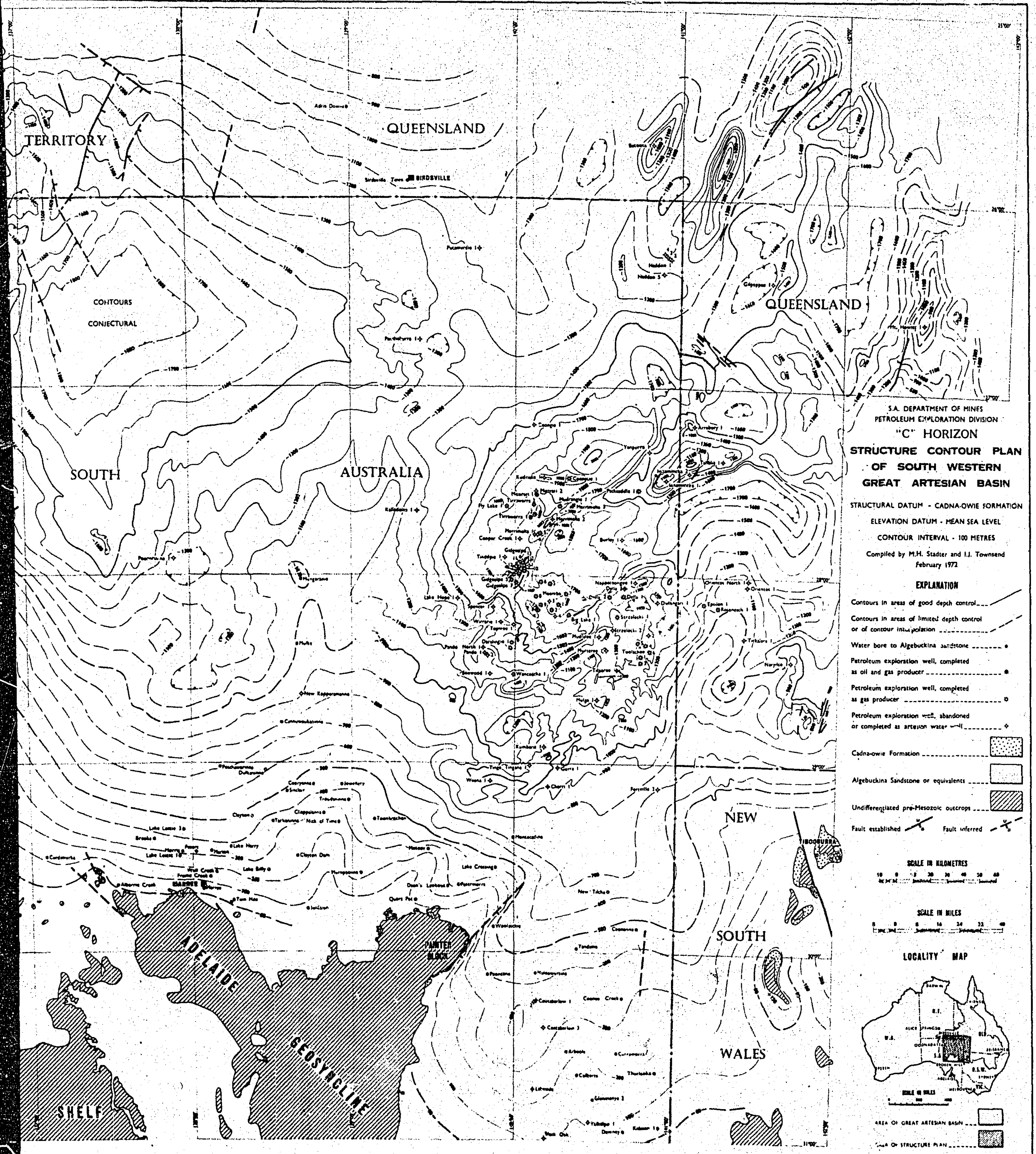


FIG. 12

PETROLEUM EXPLORATION DIVISION	**DEPARTMENT OF MINES – SOUTH AUSTRALIA**	Scale: 1:2,000,000
Compiled: M.H.S. & I.J.T.	PEDIRKA BASIN - S.A. & N.T.	Date: 7-5-73
Drn. W.J.E. | Ckd.	"C"- DEPTHS TO CADNA-OWIE FORMATION (L. CRETACEOUS) (METRES BELOW SEA LEVEL)	Drg. No. 73-262 994-2/3

2. Refraction method

(a) Determination of water-table - northern Adelaide Plains

The northern Adelaide Plains Basin is an important source of good quality groundwater which has been extensively developed for production of vegetables. Although deeper Tertiary aquifers form the main supply, water occurring in Pleistocene-Recent sand or gravel beds at depths down to 100 m is a contributing source, particularly for stock water. Figure 12 shows the results of a shallow seismic refraction probe made at Salisbury on the northern Adelaide Plains. A distinct velocity change from 534 m/s to 1720 m/s can be seen to occur at a depth of about 6.6 m. Shortly afterwards a cable-tool hole was put down to a depth of 33 m on this site. The salient points of the drilling log are also shown in Figure 12. All material encountered in the hole was classified as belonging to the Pleistocene Hindmarsh Clay Unit, and there appeared to be only minor changes in the sequence to the bottom of the hole. The significant feature was the position of the water-table, which was found to be at a depth of 6.3 m. Subsequently, the drill-hole was used for a seismic well shoot. The results agreed very closely with the refraction survey and the drilling information, as can be seen in Figure 12, although there is a slight discrepancy between the horizontal and vertical velocities of water-table sediments as measured by the refraction and well shoot methods respectively.

(b) Use of compressional and shear waves to locate water-table. Carisbrooke Reserve - northern Adelaide Plains

Although the 1720 m/s refractor described above has a compressional velocity which is characteristic of water-saturated sediments, the velocity itself is not completely diagnostic of such a situation. However, use can be made of the fact that although water has a relatively high compressional velocity, its shear velocity is almost zero. Tests were made using conventional vertical-coil geophones and special horizontally mounted geophones at another site on the northern Adelaide Plains. Again the target of interest was the water-table in the Recent-Pleistocene aquifers. The object was to measure both the compressional wave velocity (Vp) and the velocity (Vs) of the horizon-

DEPARTMENT OF MINES—SOUTH AUSTRALIA

GEOPHYSICAL METHODS IN HYDROGEOLOGY
RESULTS OF SEISMIC REFRACTION, WELL SHOOTING & DRILLING.
NORTH ADELAIDE PLAINS

COMPILED. R G N.

DRN:

CKD.

GEOPHYSICAL SERVICES

SCALE

DATE OCTOBER '76

PLAN NUMBER

S12423

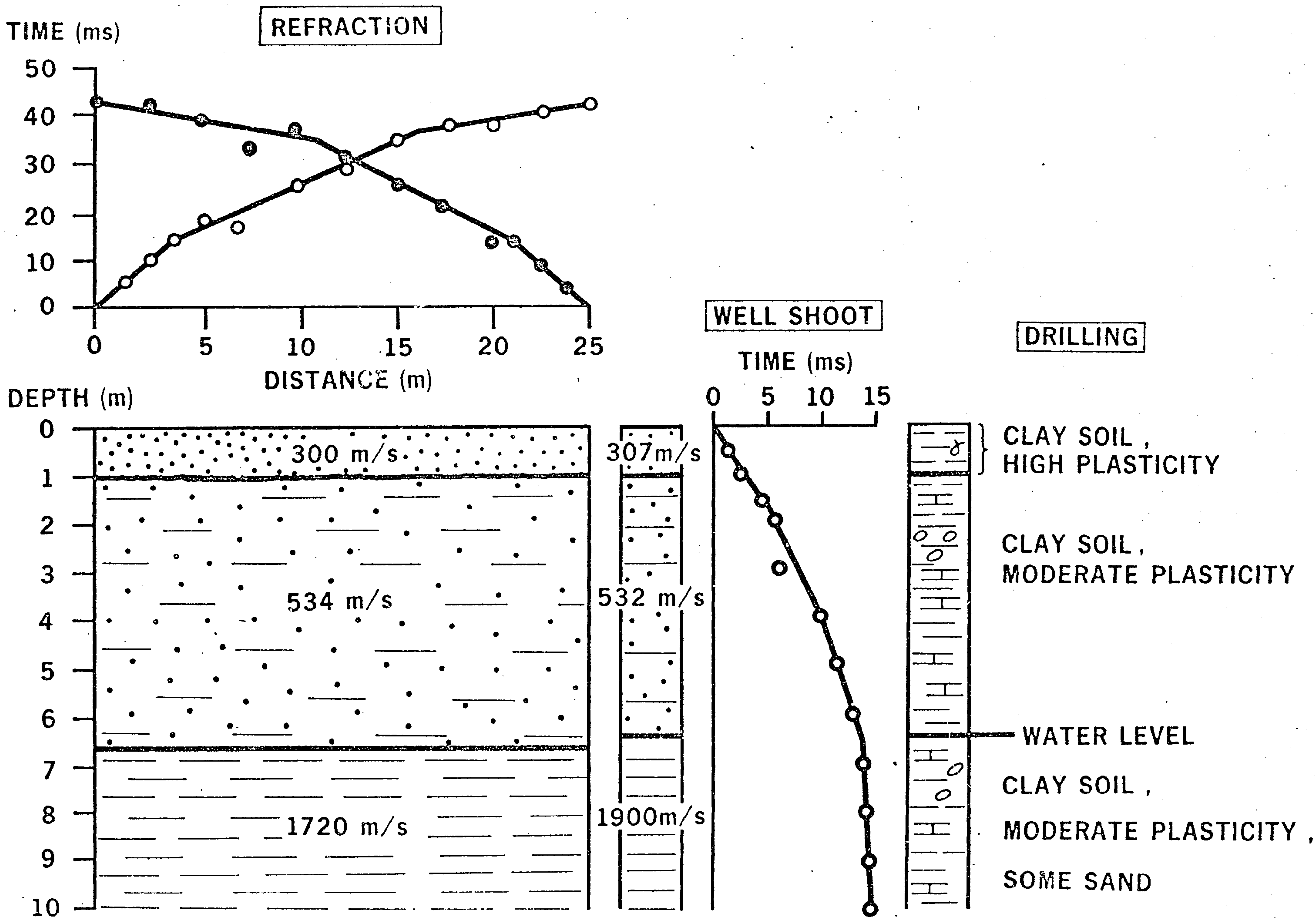


FIG.12

tally polarised shear wave. Explosives were used as energy sources, small "Anzomex" boosters in shallow auger holes being used for the vertical geophones, and strips of "Geoflex" aligned perpendicular to the traverse for the horizontal geophones. Figure 13 shows the results and interpretations of this work. The important feature is the Vp velocity of 1825 m/s for the water-saturated sediments, and the associated high Vp/Vs ratio 3.4:1. Figure 5 shows how this site fits in with a classification of lithology against Vp and Vp/Vs due to Meidav (1955).

(c) Compressional wave velocity and electrical resistivity measurements

(i) Maslin Beach - St Vincent Gulf

Figure 14 shows a comparison of seismic refraction and electrical resistivity techniques over shallow aquifers at Maslin Beach, some 45 km south of Adelaide. Again the refraction survey shows a distinct velocity change at a depth close to the unknown water-table, and the velocity of the water-saturated sands is 1890 m/s, which is within its expected range.

The resistivity probe shows high-resistivity dry surface sands underlain by a low-resistivity layer of 7 ohm-metres thought to be due to near-surface clays. The rising branch of the curve is attributed to a moist transition zone (70 ohm-metres) passing into a water-saturated zone (20 ohm-metres).

Another band of clays is interpreted as lying beneath the sandy aquifer.

Thus the two methods complement each other, although they cannot be relied on to show unequivocally the presence of a water-saturated zone.

(d) Seismic refraction and electrical resistivity methods at Mimili station - northwest South Australia

Mimili station (formerly known as Everard Park station) is located in the far northwest interior of South Australia. It is situated on the Musgrave Block, which is an uplifted area of crystalline ?Lower to Middle Adelaidean metasediments and intrusives. In this area groundwater occurs predominantly through downward percolation of surface rainfall and runoff

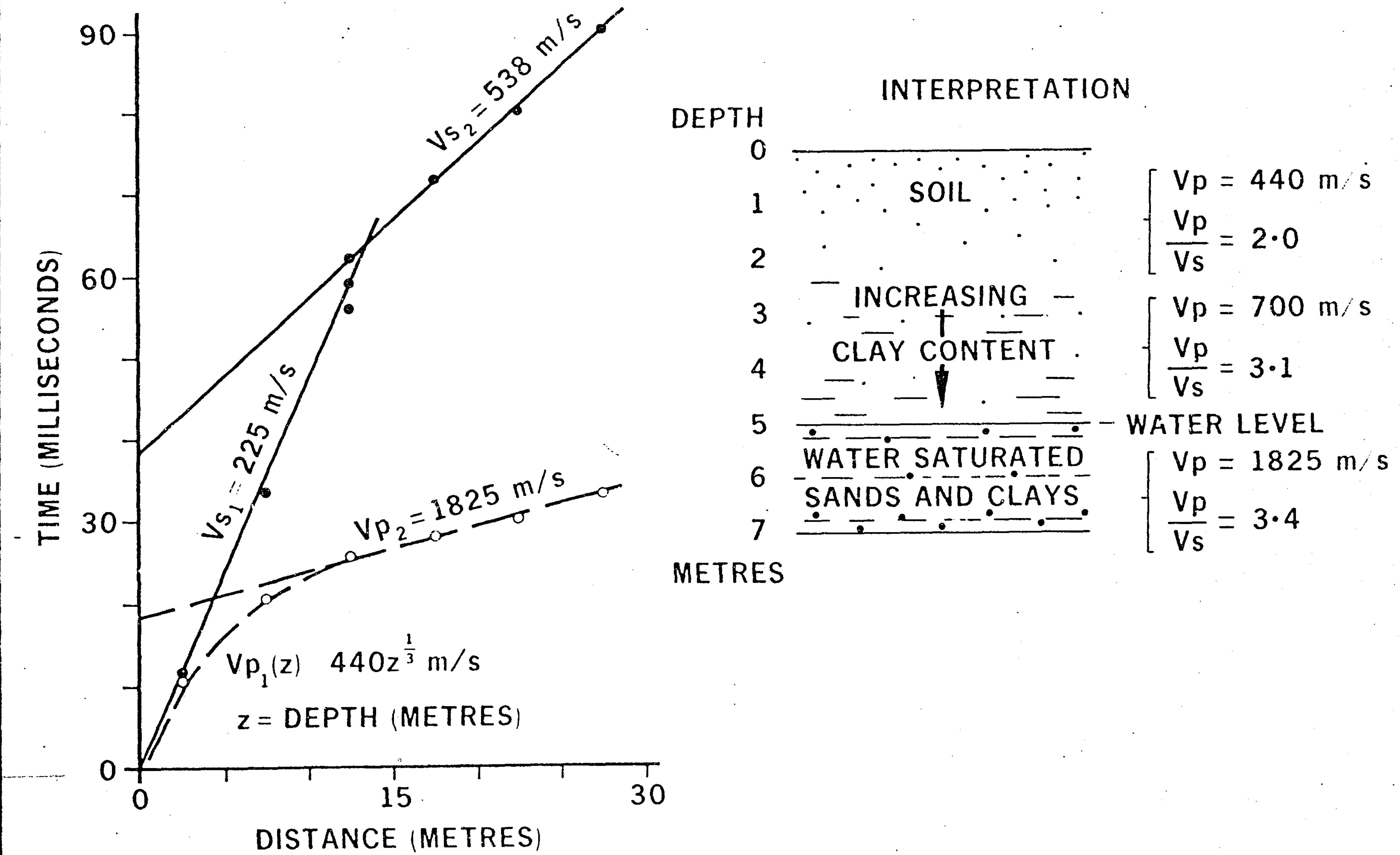


Fig. 13

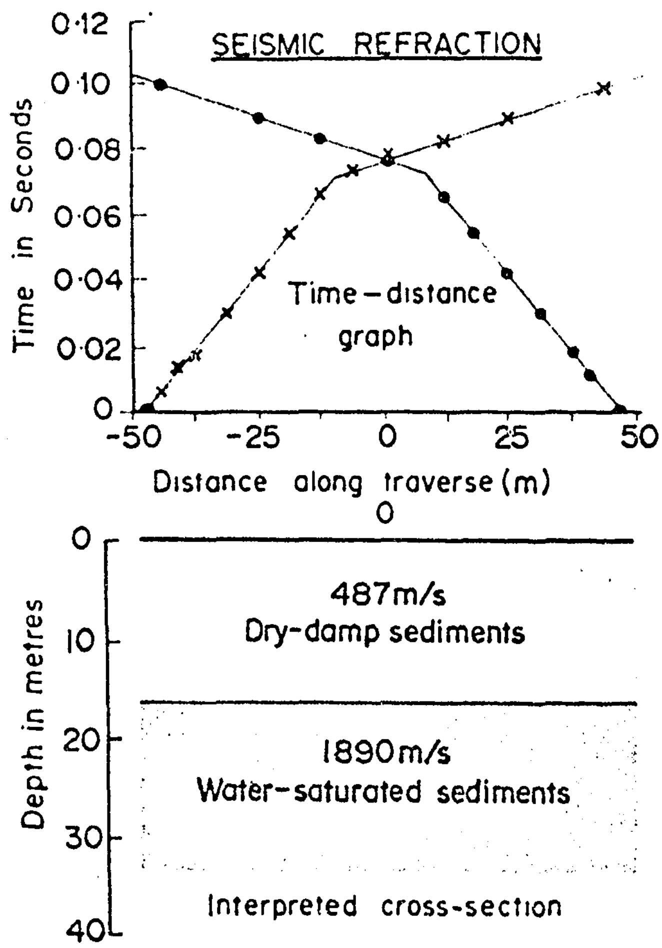
DEPARTMENT OF MINES—SOUTH AUSTRALIA

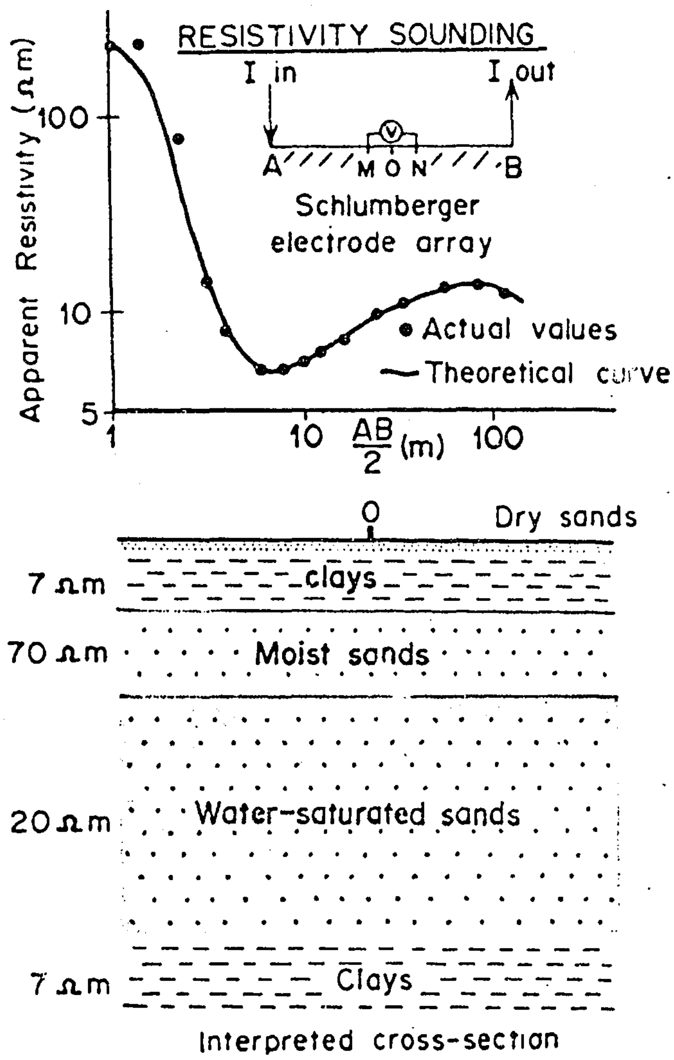
GEOPHYSICAL METHODS IN HYDROGEOLOGY
P and S WAVES
CARISBROOKE RESERVE

COMPILED RGN
DRN.
CKD.
GEOPHYSICAL SERVICES

SCALE
DATE OCTOBER '76
PLAN NUMBER S12424

Record No. 1976/108





LOCATION OF TRAVERSES

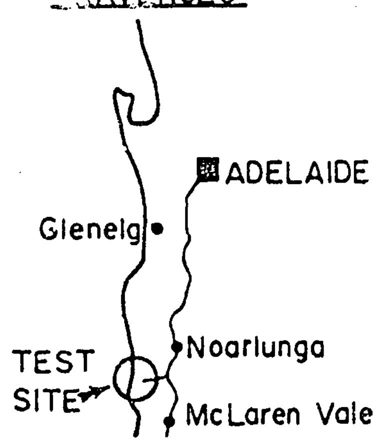


FIG.14

	DEPARTMENT OF MINES – SOUTH AUSTRALIA	SCALE
COMPILED R.G.N.	GEOPHYSICAL METHODS IN HYDROGEOLOGY SEISMIC REFRACTION & ELECTRICAL RESISTIVITY TECHNIQUES IN LOCATING WATER-TABLE	DATE OCTOBER '76
DRN CKD		PLAN NUMBER S12425
GEOPHYSICAL SERVICES		

from the ranges. It collects and is stored in shallow aquifers (sand and gravel) which are found in the alluvia and colluvia of outwash fans or in bedrock depressions in the valleys between the ranges. The particular section examined here is a bedrock depression in a valley between two of the hilly granite inselbergs which form the Everard Ranges.

A combination of methods was used to outline bedrock configuration. Initially a constant-separation electrical resistivity traverse using the Schlumberger array was made over the section. The current electrode separation was made large enough so that apparent-resistivity values were inversely proportional to total longitudinal conductance of sediments above basement in the section. Using the lowest apparent-resistivity value as a guide, the deepest part of the section was located, and an expanding electrical depth probe was made here. The interpretation of the depth probe is shown in Figure 16. An average value for the resistivity of sediments overlying bedrock was calculated from this and used to convert apparent-resistivity values of the horizontal traverse to depth estimates.

Following this, three seismic refraction spreads were made at intervals along the traverse. The results from these were used to plot a seismic cross-section of the valley floor (see Fig. 15). Figure 16 compares seismic and resistivity results at the deepest point. A combination of a seismic velocity of 2020 m/s and a resistivity of 40 ohm-metres for the thickest layer was thought to be a good indication that this part of the section might consist of water-saturated sediments, although the resistivity value implied low-salinity water (possibly less than 1000 ppm), which would have been unusual for bore water in this vicinity. Subsequent drilling disproved this hypothesis. A log of the drill-hole shown in Figure 15 shows that while the interpreted depths to unweathered bedrock are good, the thickest layer consists mostly of weathered granite gneiss. Although water was cut at 34 m the supply was too poor to warrant further development. The results of a magnetic traverse made over the same section showed anomalies in the eastern part that could be interpreted as being due to basic dykes at depths of about 30 m. Drilling was recommended to test these, as basic dykes in the area are known to act as groundwater traps. However, at this date no drilling has been carried out on these.

DEPARTMENT OF MINES—SOUTH AUSTRALIA

GEOPHYSICAL METHODS IN HYDROGEOLOGY
MIMILI TRAVERSE CST 1
RESISTIVITY & MAGNETIC TRAVERSES

COMPILED: R G N

DRN: L.C | CKD.

GEOPHYSICAL SERVICES

SCALE

DATE OCTOBER '76

PLAN NUMBER S12 481

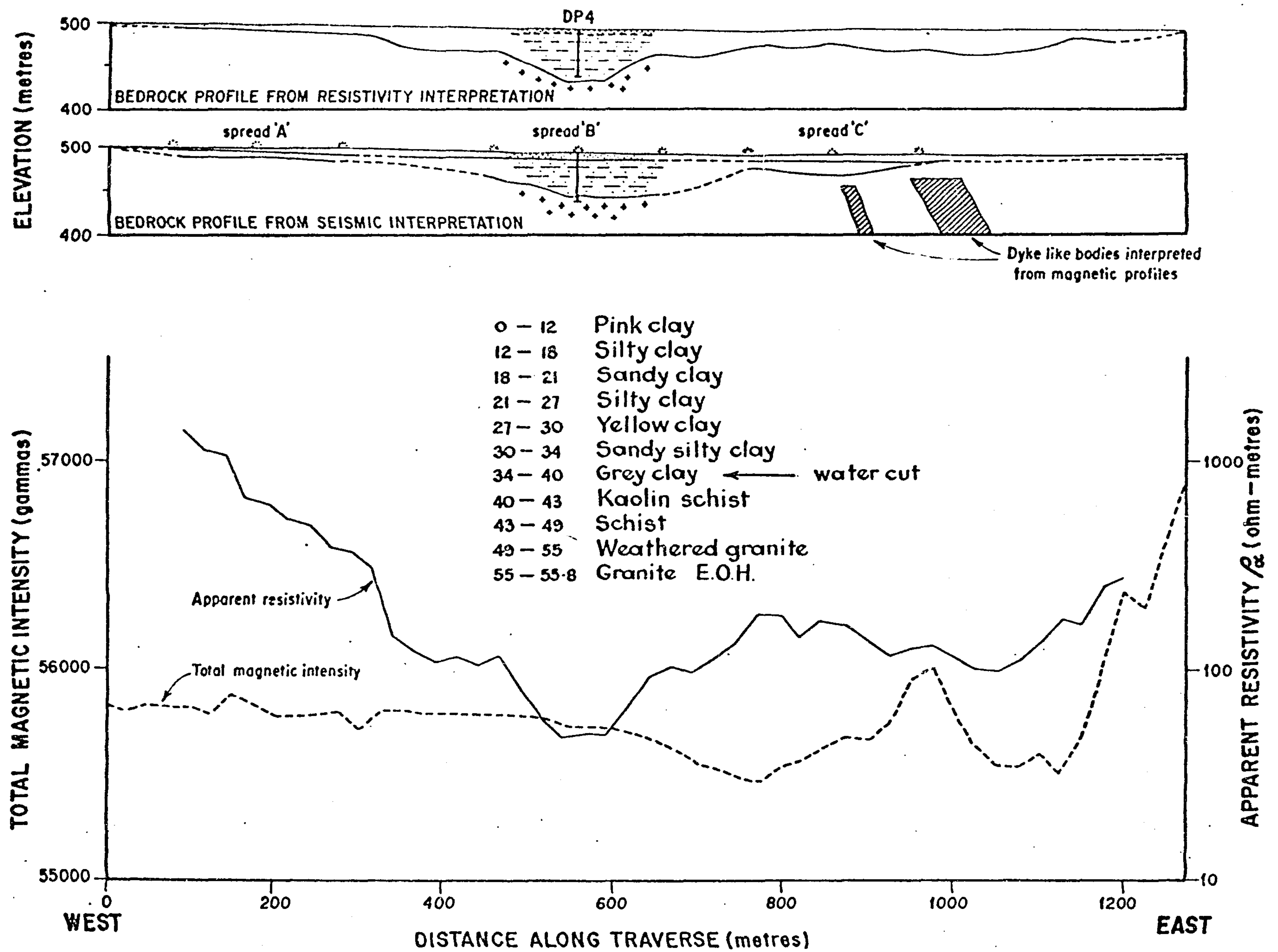
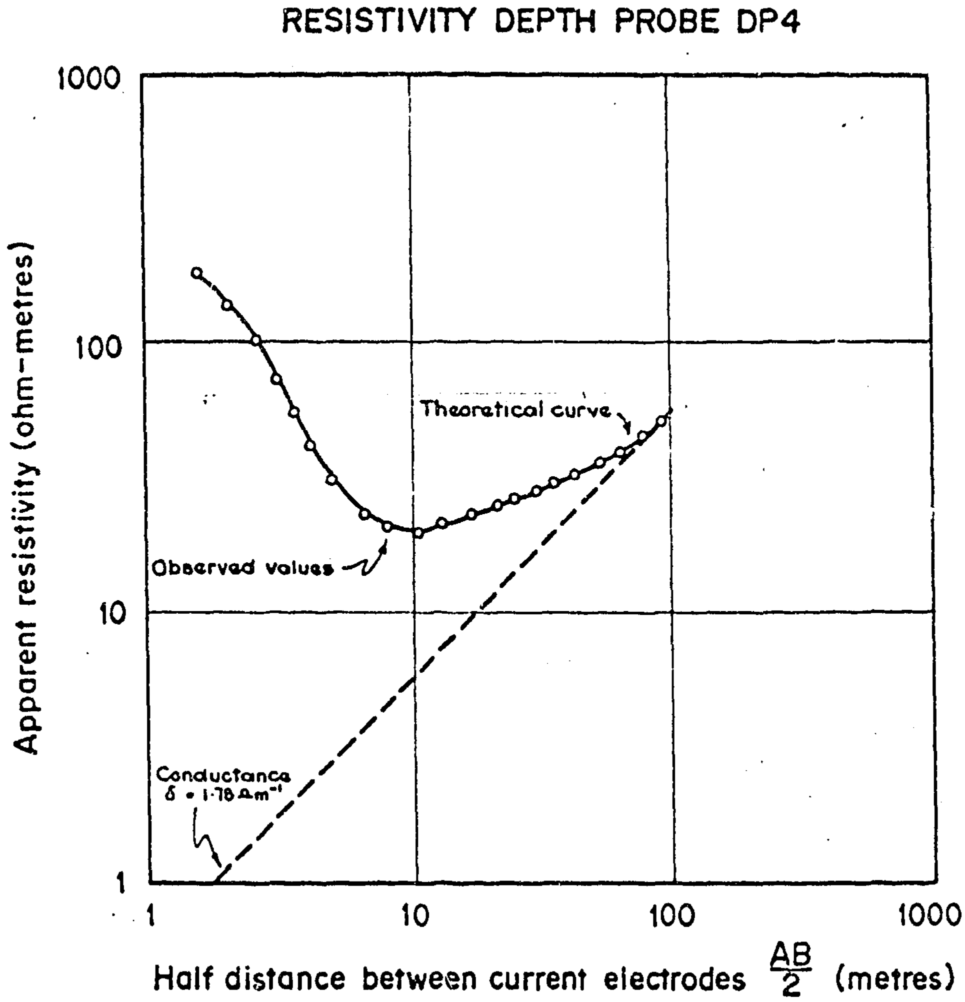


FIG.15



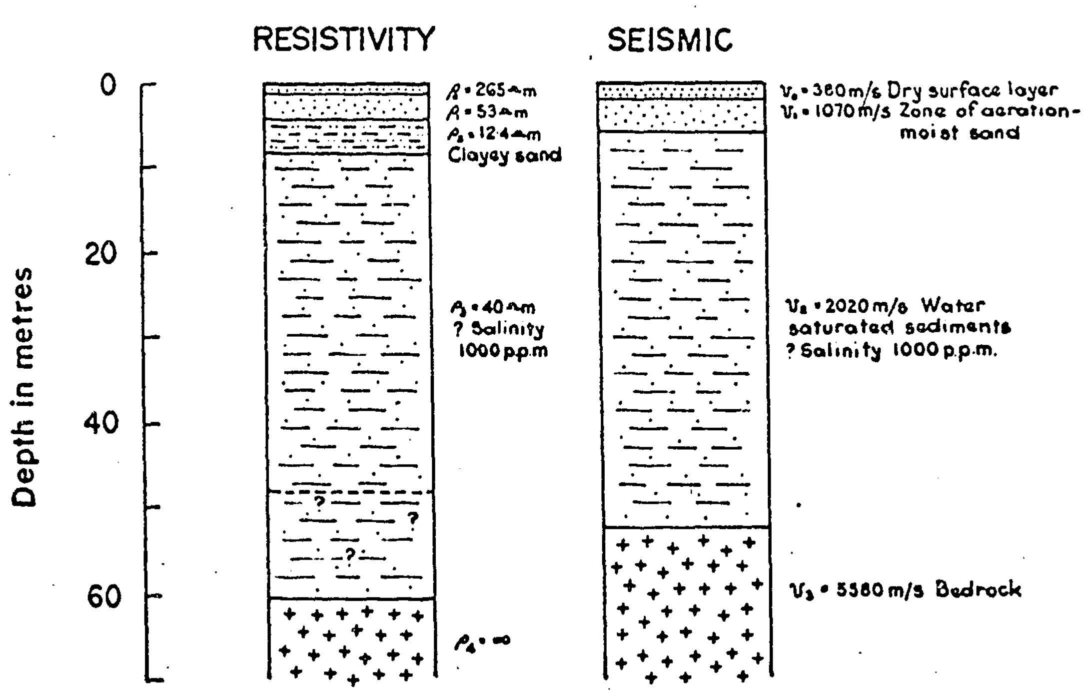


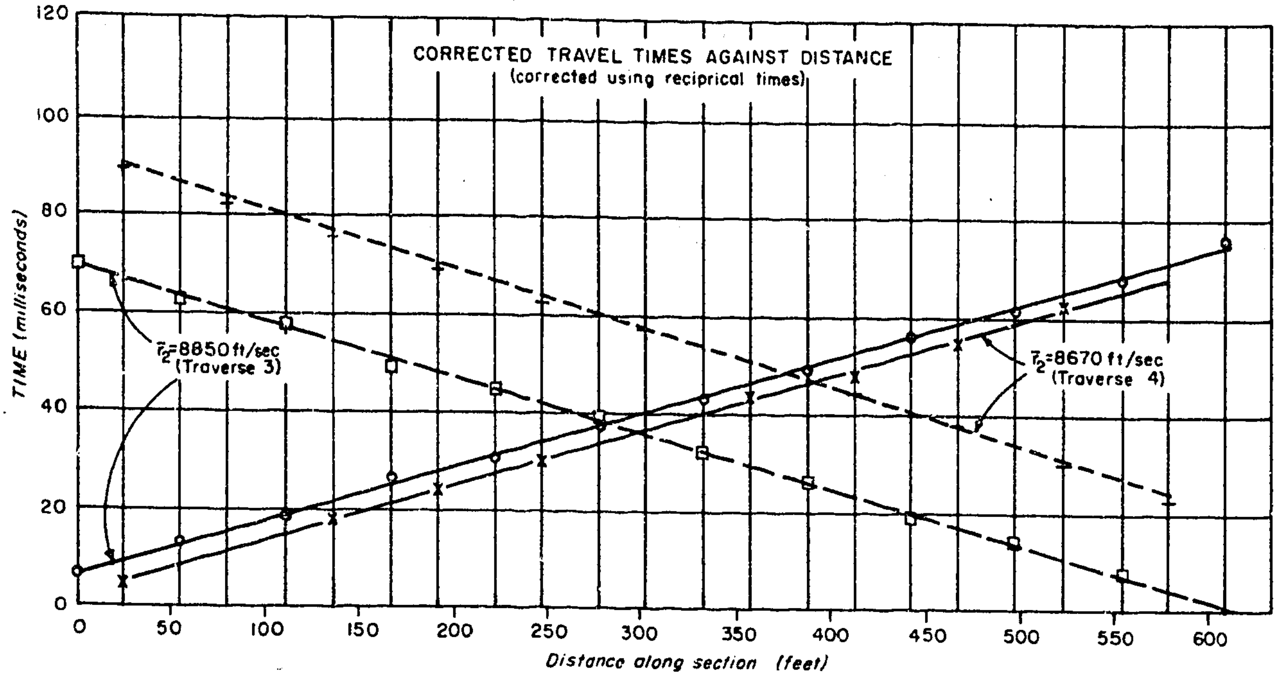
FIG.16

	DEPARTMENT OF MINES—SOUTH AUSTRALIA	SCALE
COMPILED: RGN	GEOPHYSICAL METHODS IN HYDROGEOLOGY MIMILI—TRAVERSE CST 1 RESISTIVITY & SEISMIC DEPTH PROBES	DATE OCTOBER '76
DRN: L.C. CKD.		PLAN NUMBER
GEOPHYSICAL SERVICES		S12426

(e) Anomalously low velocities in water-saturated sediments, Aroona Dam - Flinders Ranges, South Australia

Although not connected with the search for groundwater this case is interesting because it shows that under certain circumstances velocities measured in apparently water-saturated sediments can be considerably less than expected. The work at Aroona Dam was done to test bedrock conditions in the upper reaches of the dam for possible construction of a silt trap dam. Three seismic refraction spreads and one resistivity depth probe were made in the area of interest, which at the time was covered with a few metres of water. The analysis of reciprocal shots on one of the refraction spreads is shown in Figure 17; it is a good example of how the true bedrock velocity of 2680 m/s can be determined from actual time-distance curves which appear as an irregular set of points due to bedrock topography changes. The time-depths to bedrock appear in the middle of the figure (under "$\Delta/2$") as time in milliseconds. A depth conversion factor, which depends mainly on the velocity of the sediments overlying bedrock, is required to convert these to actual depths. Figure 18 shows how this will vary according to overburden velocity. Now, velocities as measured in the muds range from 300 m/s in muds exposed on shore to about 875 m/s where they were covered with 3 m of water. These appear to be anomalously low for water-saturated sediments. However, if we had assumed a velocity of 1500 m/s for them the resulting calculated maximum depth to bedrock would be 66 m. Now the resistivity depth probe gave a depth to resistive bedrock of 38 m in the middle of the valley; this depth agrees much more closely with the seismic depth of 30 m arrived at by using a velocity of 875 m/s at this point.

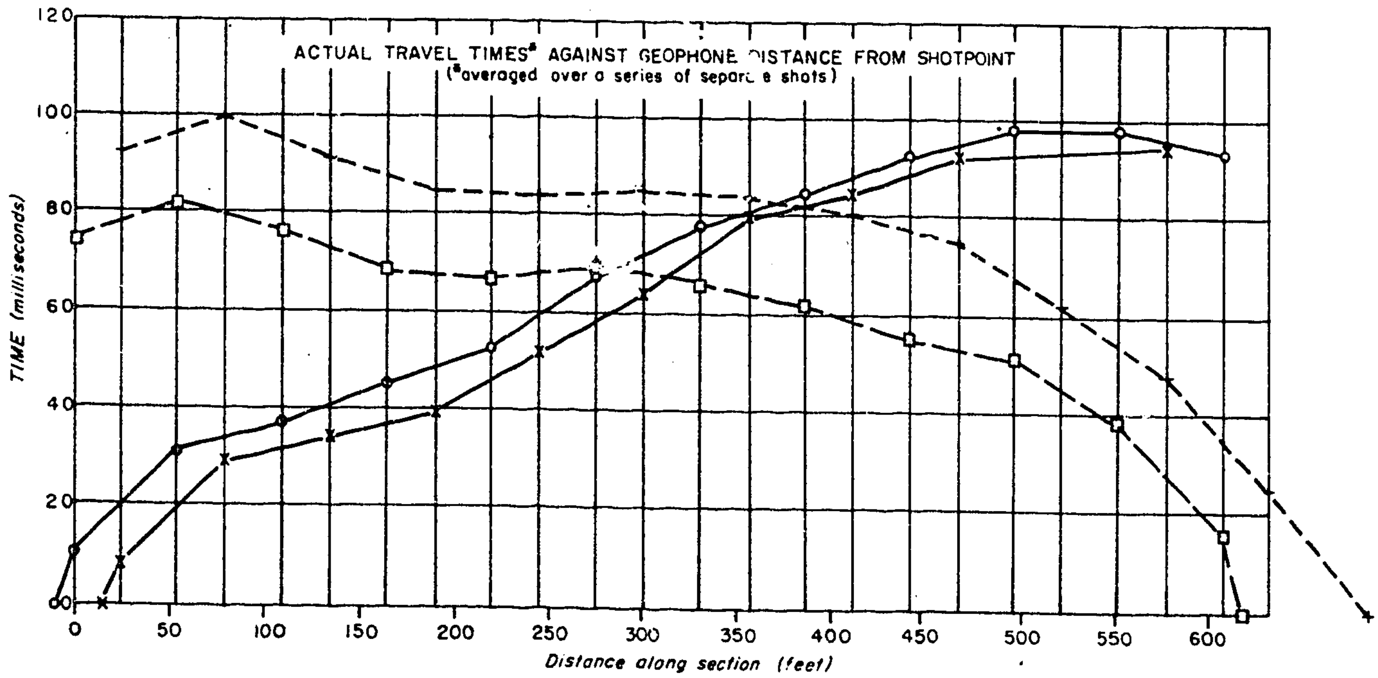
It therefore appears that the silts and sands have anomalously low velocities even though they are water-saturated. This is in agreement with the work of Press & Ewing (1948) who showed that a low-speed layer can exist in water-covered areas, just as the so-called "weathered" layer, with velocities often less than that of air, can exist on land. Press & Ewing suggest that a low-velocity bottom is most likely to be found in areas of rapid deposition. Certainly this is the case at Aroona Dam, which has lost one quarter of its original capacity in only 20 years, due to siltation.



A — RECIPROCAL ANALYSIS — A'

t_1	11·0	8·5	31·5	29·5	37·0	34·5	45·0	39·5	52·8	52·5	67·3	64·3
t_2	74·5	32·5	81·5	99·8	76·2	91·9	68·4	84·7	66·9	84·4	69·4	85·2
$\Delta/2$	4·8	3·8	18·5	17·9	18·6	16·5	18·7	15·4	21·9	21·7	30·4	28·0
t_1'	6·3	4·8	13·0	11·6	10·4	18·1	26·3	24·2	31·0	30·8	37·0	36·3
t_2'	69·8	88·8	63·0	81·9	57·6	75·5	49·7	69·4	45·1	62·7	39·1	57·2

t_1	77·8	79·8	84·6	84·3	92·3	92·3	98·0	93·8	98·0	94·6	93·0	
t_2	66·4	84·2	61·9	81·3	55·1	75·8	50·8	62·3	38·3	48·0	15·8	25·2
$\Delta/2$	34·1	35·3	35·3	36·1	35·7	37·3	36·4	31·3	30·2	24·6	16·4	
t_1'	43·7	44·6	49·4	48·3	56·6	55·0	61·6	62·5	67·9	70·1	76·6	
t_2'	32·3	49·0	26·7	45·3	19·4	38·5	[illegible]	31·0	8·2	23·5	0·0	



+ □ o X Shot points

t_1, t_2 } Actual travel times

$\Delta/2$ Time depth

t_1', t_2' } Corrected travel times

then $\Delta/2 = 1/2\,(t_1 + t_2 - t_{s's''})$

where $t_{s's''}$ = reciprocal time (shot point' to shot point'')

→ $t_1' = t_1 - \Delta/2$ and $t_2' = t_3 - \Delta/2$

AROONA DAM SEISMIC SURVEY

SEISMIC TRAVEL TIMES AND RECIPROCAL ANALYSIS
GEOPHYSICAL SECTION AA'-DAM CENTRE LINE

Record No.1976/108

(Based on Dept. Mines S.A. dwg No 74-476)

AROONA DAM SEISMIC SURVEY

VARIATION OF DEPTH CONVERSION FACTOR (K) WITH VELOCITY OF OVERBURDEN (V_0)

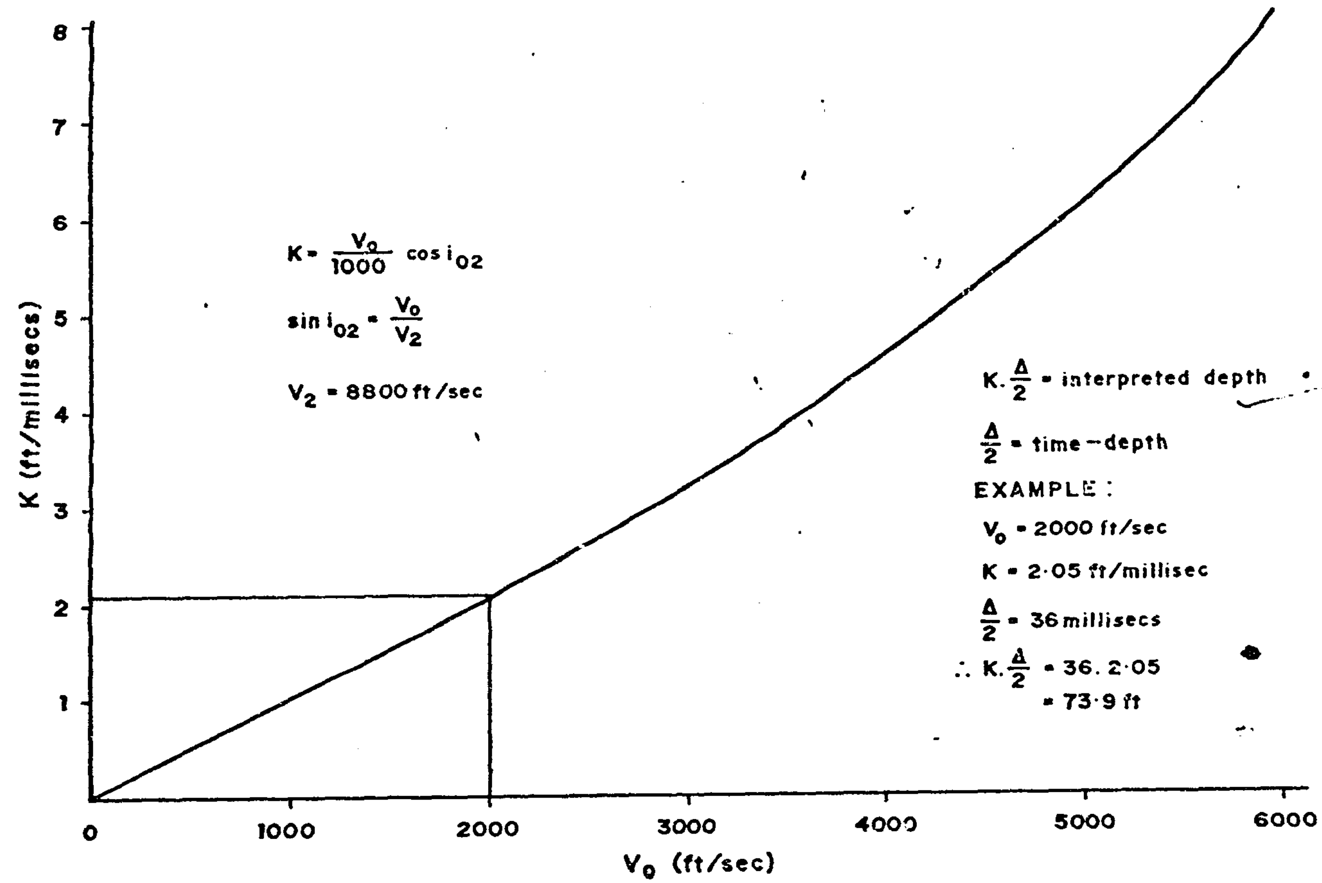


FIG. 18

(f) Uses of reciprocal shootin

(i) Detection of shear zones by reciprocal shooting

Figure 19 shows how a sheared zone was detected in a cutting on the South Eastern Freeway in the Mount Lofty Ranges east of Adelaide by reciprocal seismic shooting and velocity analysis of bedrock. Although this example is again not related to the search for groundwater, it does show the potential of the method where groundwater is contained within shear zones. In connection with this, the work of Wyllie, Gregory & Gardner (1956), is worth mentioning. In order to test the theory that poor coupling or cracks in materials can cause great decreases in velocities, they measured the velocities of a stack of glass microscope slides. Along the length and breadth of the stack velocities agreed with similar measurements for a single slide at about 5350 m/s. The velocity measured across a stack of 50 slides gave a value of only 503 m/s. Across 25 slides the velocity was not much higher, and even with only two or three slides the velocity was only of the order of 2400 m/s, being poorly determinate. Manual pressure did not change these velocities materially. However, when the faces of the slides were wet before being assembled into a pile a true value of the velocity of the glass was obtained. This suggests that wet shear zones may need to contain fairly large fissures before they show a significantly decreased seismic velocity.

(ii) Mapping of bedrock topography by reciprocal shooting

Reciprocal shooting can be useful when a profile of bedrock topography in basins is desired, e.g. when prospecting for buried channels.

Figure 20 shows the results of such a survey made over a Tertiary basin on Eyre Peninsula. The Tertiary sequence consisted of horizontally bedded clays and sand-gravel beds with occasional peat and lignite beds extending to depths at least 150 m. Metamorphic rocks of the Proterozoic Flinders Group formed bedrock in the area; these were mostly gneissic. Examination of the time-distance curves showed that there were three main refracting horizons of interest:

- the zone of aeration (soil and sediments above the water-table) (300 to 500 m/s).

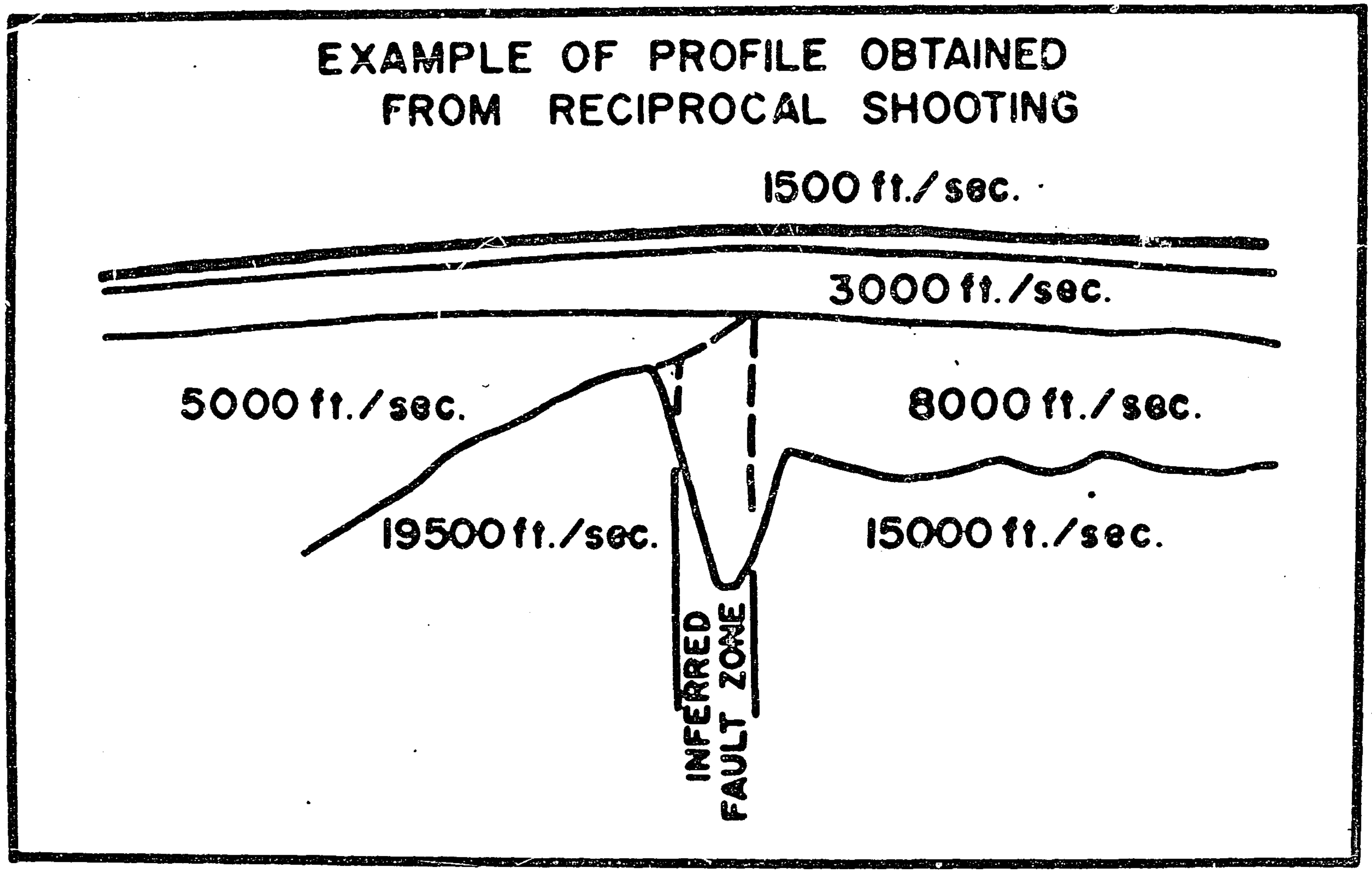

EXAMPLE OF PROFILE OBTAINED
FROM RECIPROCAL SHOOTING
1500 ft./sec.
3000 ft./sec.
5000 ft./sec.
8000 ft./sec.
19500 ft./sec.
15000 ft./sec.
INFERRED
FAULT ZONE

FIG. 19.

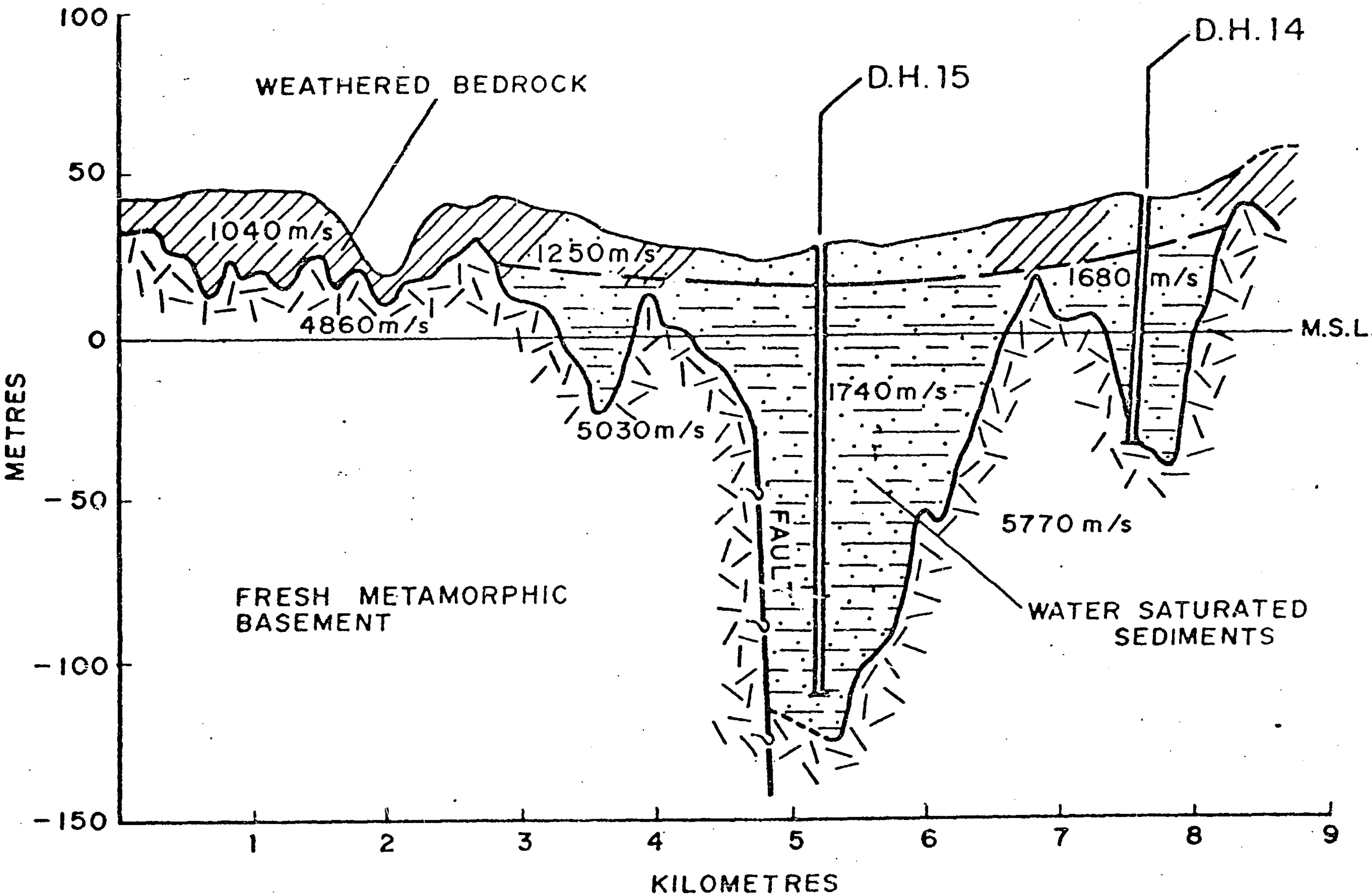


FIG.20

DEPARTMENT OF MINES–SOUTH AUSTRALIA

GEOPHYSICAL METHODS IN HYDROGEOLOGY
EYRE PENINSULA
SEISMIC TRAVERSE

COMPILED: R.G.N.
DRN.: CKD:
GEOPHYSICAL SERVICES

SCALE
DATE: OCTOBER '76
PLAN NUMBER: S12427

- water-saturated sediments below the water-table (1600 to 1800 m/s).
- basement refractor (5000 to 6000 m/s)

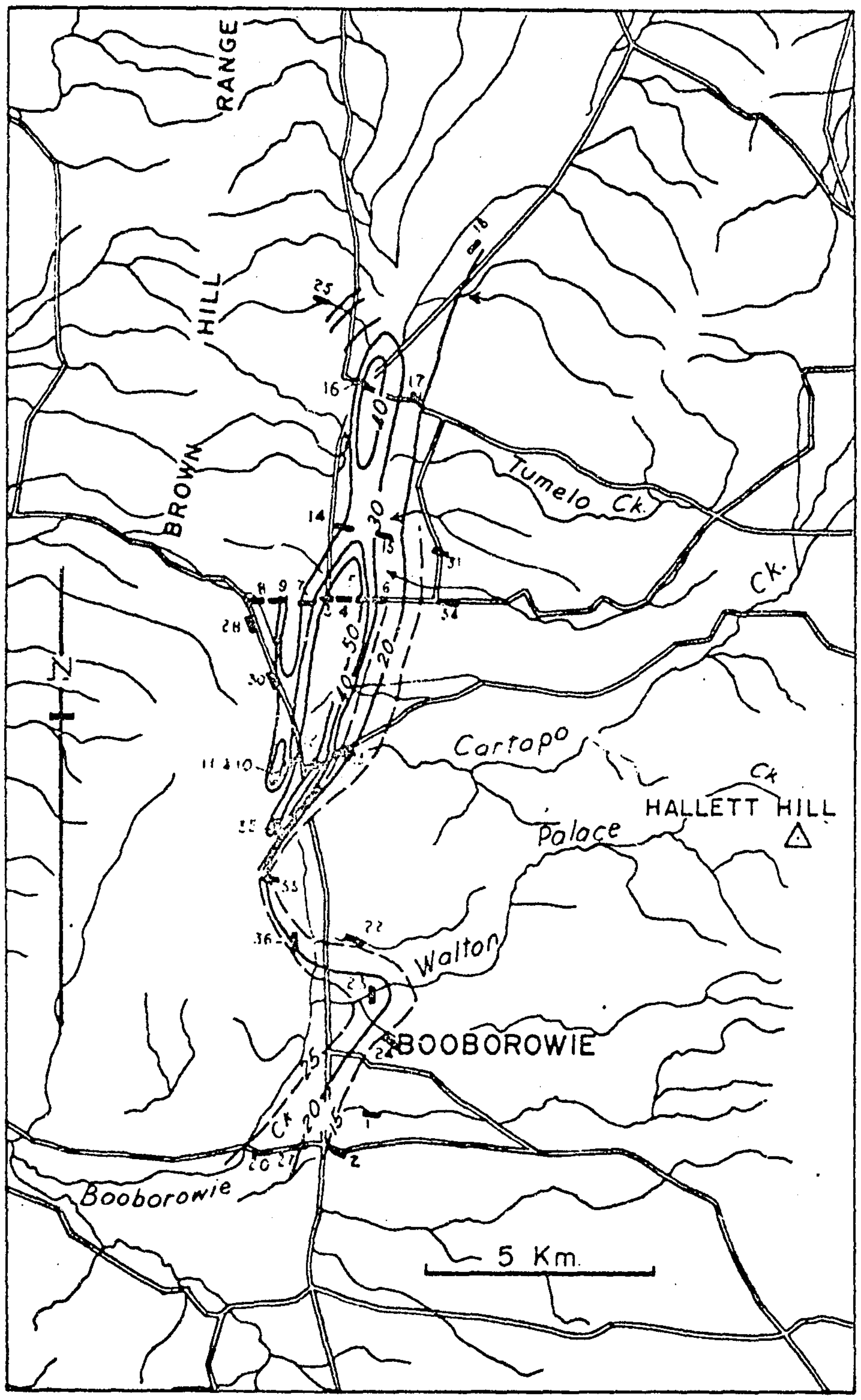
Time-depths to basement from each geophone at the surface were obtained from forward and reverse refractions. These were converted to depths by using measured velocities in the vicinity of the geophone, and thence a profile of bedrock topography was prepared. The palaeochannels detected by these waves were verified by extensive drilling and it was possible to chart them over many kilometres.

(g) General basin studies using seismic refraction

(i) Booborowie Valley (see Figs. 21 and 22)

Booborowie Valley lies about 160 km north of Adelaide. The district is one of the largest producers of lucerne seed in South Australia. The valley itself trends north and is infilled to about 50 m by poorly sorted piedmont gravel, silt, and clay of Pleistocene to Recent age. The bedrock underlying and marginal to the valley consists of laminated slate, siltstone, tillite, sandstone, and quartzite of Proterozoic age, having a steep westerly dip. Because of declining water levels, a project was begun to produce a water budget for the area to help in long-term management. Regular monitoring of water-levels in 53 observation bores was carried out. Detailed geological mapping of the hills enclosing the valley was made. However, very few of the existing bores in the valley had reached bedrock as adequate supplies of water had always been found within a few metres of the surface. Therefore, it was proposed that five stratigraphic drill-holes be put down along the axis of the valley. Inspection of the outcrop pattern suggested that these would be insufficient to define adequately the bedrock configuration, although they would suffice for hydrogeological data, and so 30 seismic refraction spreads were made at points over the valley. The results from these were used to help site the stratigraphic bores, and, with the stratigraphic control these provided plus the hydraulic properties of the aquifer derived from pump testing, a good picture was established of the bedrock configuration and capacity of the valley. As a comparison of costs, the cost of drilling and pump testing the stratigraphic holes was $11,300, while the cost of the seismic work was $3000 (1973 prices).

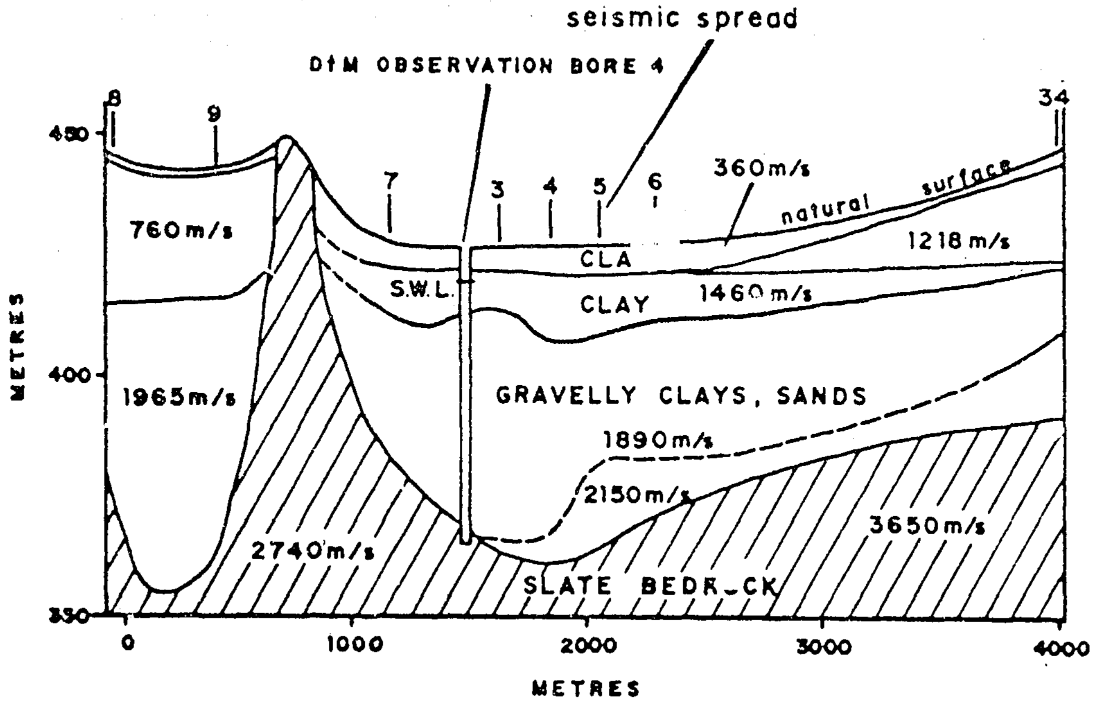
(90)



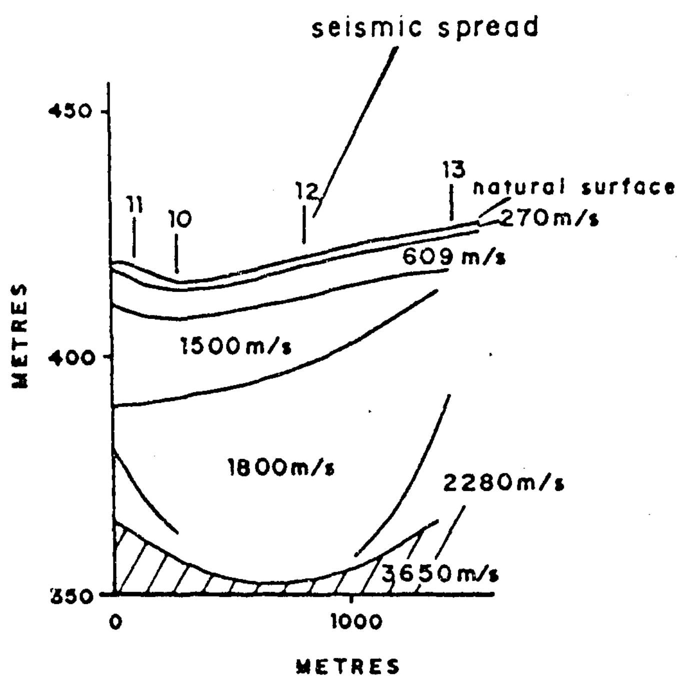
10m. CONTOUR .... —20—
5m. CONTOUR .... --15--
SEISMIC SPREAD .... ▬20

FIG.21

	DEPARTMENT OF MINES—SOUTH AUSTRALIA	SCALE
COMPILED: R.G.N	GEOPHYSICAL METHODS IN HYDROGEOLOGY	DATE OCTOBER '76
DRN. / CKD.	BOOBOROWIE VALLEY SEISMIC SURVEY	PLAN NUMBER
GEOPHYSICAL SERVICES	ISOPACHS OF WATER SATURATED SEDIMENTS	S12428



SECTION THROUGH SPREADS 3–9,34



SECTION THROUGH SPREADS 10–13

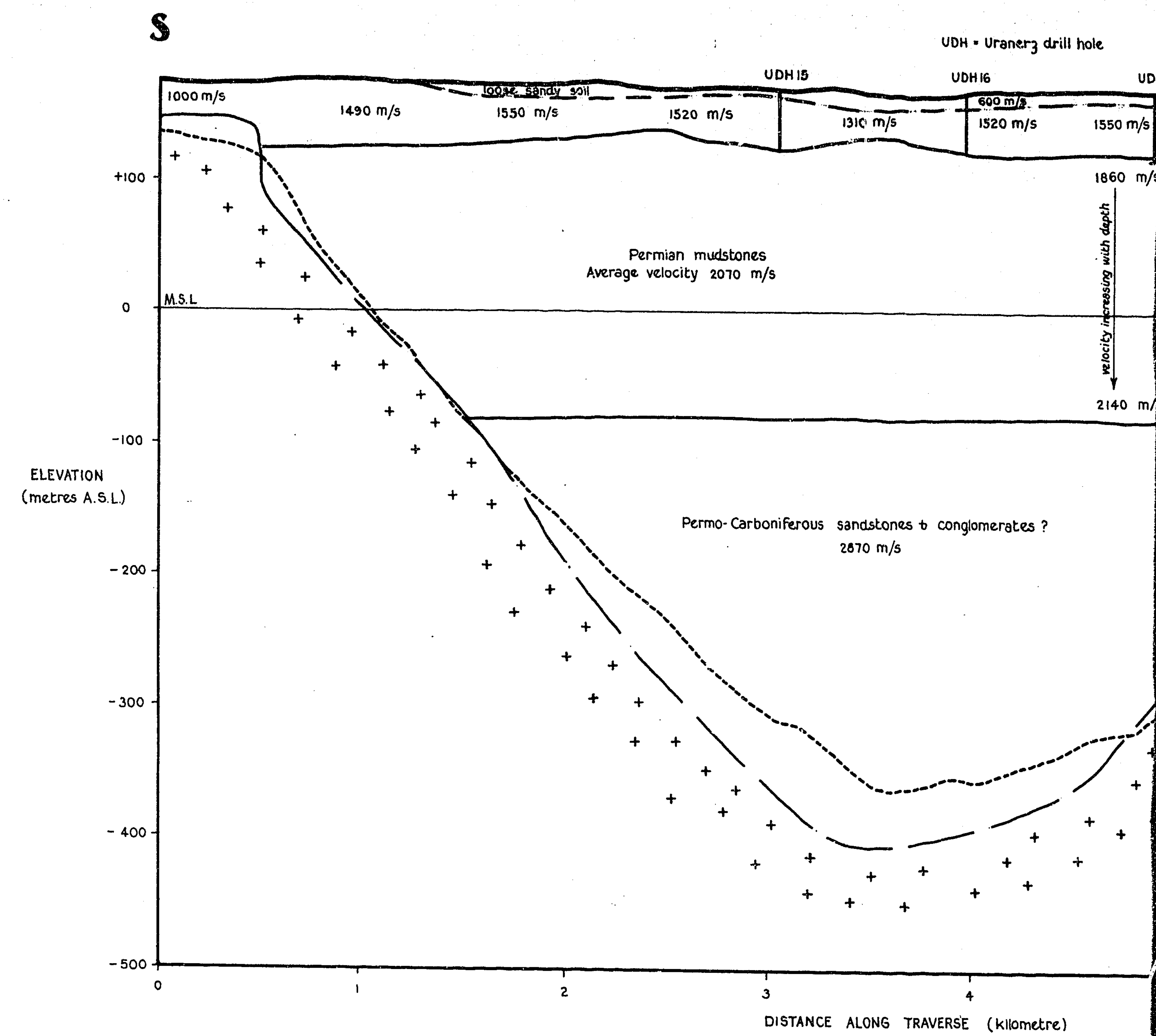
FIG.22

	DEPARTMENT OF MINES – SOUTH AUSTRALIA	SCALE.
COMPILED: R.G.N.	GEOPHYSICAL METHODS IN HYDROGEOLOGY BOOBOROWIE VALLEY SEISMIC SURVEY SECTIONS THROUGH SEISMIC SPREADS	DATE: OCTOBER '76
DRN: CKD.		PLAN NUMBER:
GEOPHYSICAL SERVICES		S 12429

(ii) <u>The Durkin Trough</u> (otherwise known as the Mulgathing Trough).

Although this survey was not conducted for hydrogeological purposes, it serves to show how gravity and seismic methods can be applied to determine basin configuration and density of the sediments infilling the basin. It may, therefore, be possible to derive some estimate of porosities of basin sediments by using these two techniques together.

The Durkin Trough is a Permian trough located near Tarcoola in the northwest of South Australia. It lies within the Gawler Block, a platform of Precambrian crystalline basement rocks which includes Eyre Peninsula and a large area to the north. In the vicinity of the trough, basement rocks are predominantly metamorphic rocks of probably Lower Proterozoic age with velocities around 5900 m/s. A sequence of Permo-Carboniferous sediments overlain by about 50 m of Tertiary sandstone and siltstone (velocity about 1500 m/s) provides infill for the trough. Palynological examination has been made of mudstones comprising the upper 250 m of the Permian sequence and a correlation is suggested between the lower part of this and the Boorthanna Formation of the Arckaringa Basin and between the upper part and the Stuart Range Formation of the same basin. There are no velocity discontinuities which would indicate distinct refracting seismic horizons in these mudstones, but rather a smooth increase with depth in seismic velocity from 1800 m/s to 2140 m/s. However, there is evidence of a further refractor having a velocity of 2700 m/s at depths greater than 250 m in the deeper parts of the trough. It has been suggested that this is the equivalent of the coarse clastic beds of the lower part of the Boorthanna Formation. Seismic refraction was used on five traverses, about 10 km apart, to outline the shape and depth of the trough (see Fig. 23). Gravity readings were then made on three of the traverses. A linear regional effect was removed from the gravity profile and then residual gravity data were plotted against the seismic depth estimates (see Fig. 24). Now, Rieke & Chilingarian (1974, pp. 103-106) suggest that for argillaceous sediments the density should increase exponentially with depth of burial. Therefore, an exponential function was fitted by least-squares to these data. Lines representing the gravity effect of infinite slabs of homogeneous material having various density contrasts were drawn on the graph, and their intersections with the exponential function were noted and used to



S
UDH = Uranerz drill hole
UDH 15
UDH 16
loose sandy soil
1000 m/s
1490 m/s
1550 m/s
1520 m/s
1310 m/s
600 m/s
1520 m/s
1550 m/s
1860 m/s
velocity increasing with depth
2140 m/s
Permian mudstones
Average velocity 2070 m/s
M.S.L.
Permo-Carboniferous sandstones & conglomerates ?
2870 m/s
ELEVATION
(metres A.S.L.)
+100
0
-100
-200
-300
-400
-500
0
1
2
3
4
DISTANCE ALONG TRAVERSE (kilometre)

5637, 5737

(55)

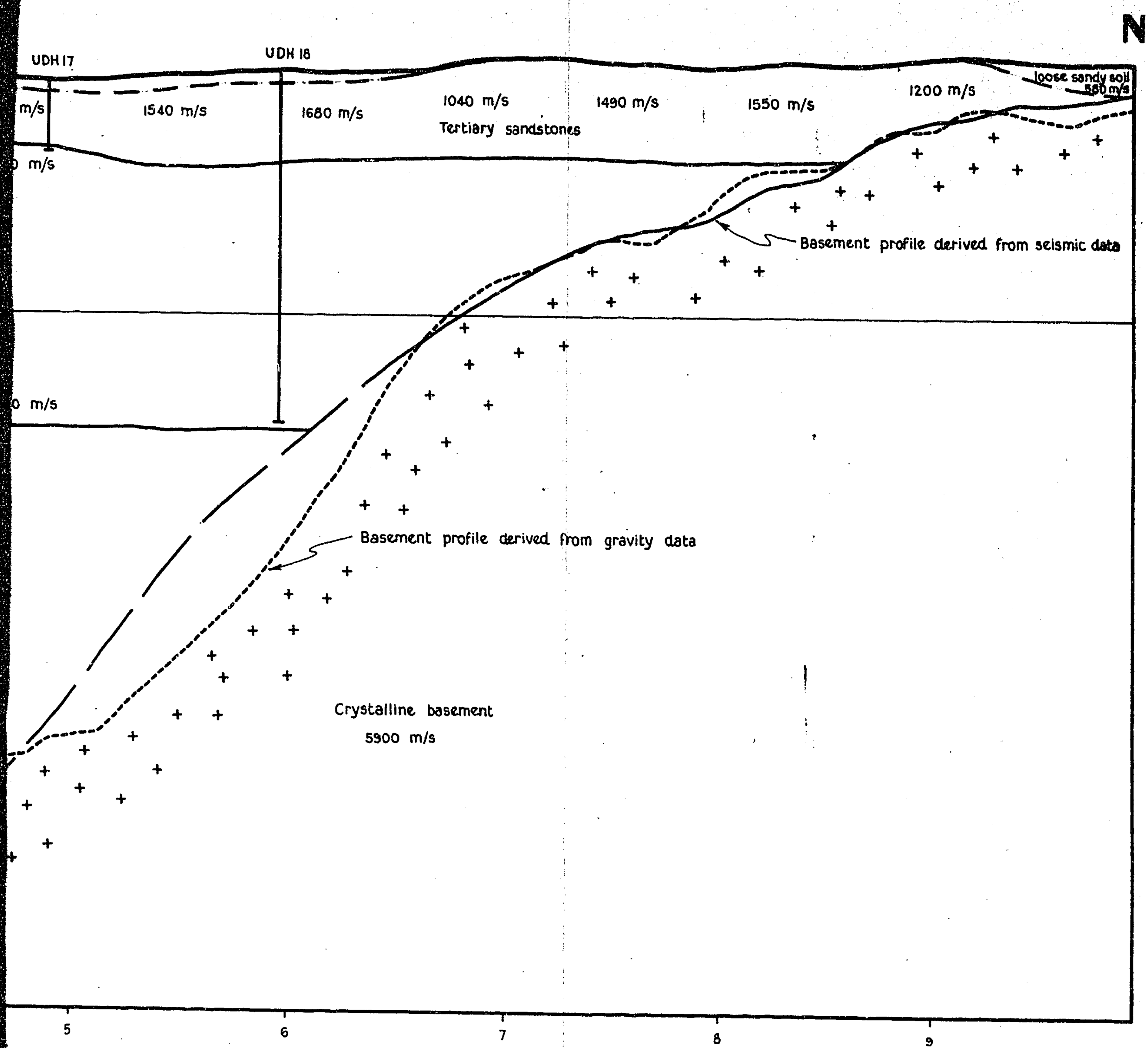


FIG. 23

DEPARTMENT OF MINES — SOUTH AUSTRALIA

MULGATHING GEOPHYSICAL SURVEY
TRAVERSE 5
CROSS-SECTION FROM SEISMIC & GRAVITY DATA

GEOPHYSICS SERVICES SECTION	R. NELSON GEOPHYSICIST	Drn. R.N.	SCALE: horizontal 1:25 000 vertical 1:4000
		Tcd. L.C.	75-279
		Ckd. A.F.	
Director of Mines		Exd.	DATE: MARCH '75

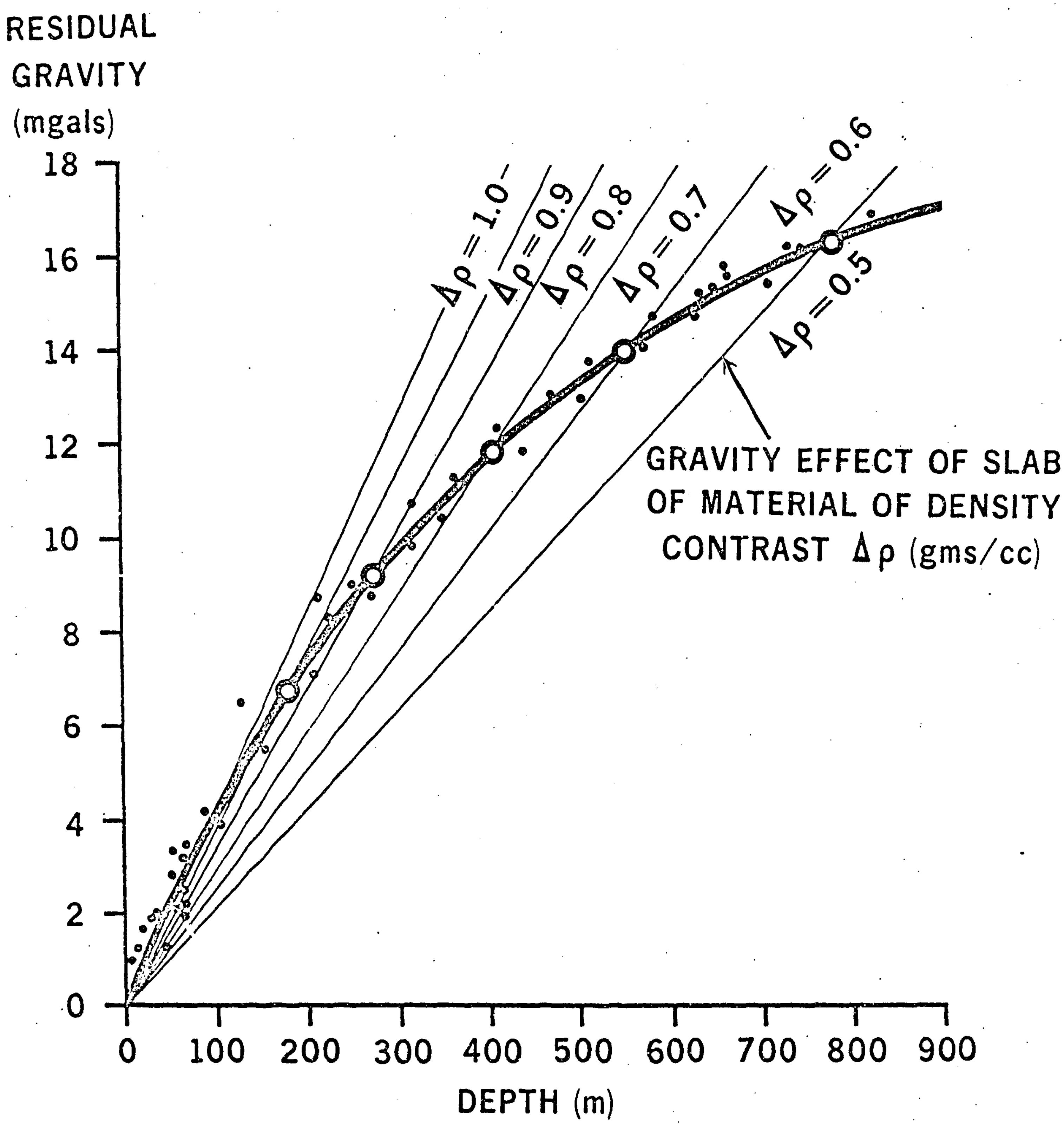


FIG.24

		DEPARTMENT OF MINES – SOUTH AUSTRALIA	SCALE
COMPILED: R.G.N		GEOPHYSICAL METHODS IN HYDROGEOLOGY DURKIN TROUGH RESIDUAL GRAVITY Vs. SEISMIC DEPTH	DATE OCTOBER '76
DRN:	CKD.		PLAN NUMBER S12430
GEOPHYSICAL SERVICES			

plot a function relating density contrasts to depth. Since a density of 2.7 g/cm^3 had been assumed for the basement rocks it was then possible to derive a function relating density of the Permian mudstones to depth (see Fig. 25). Although no attempt has been made here to relate velocities and densities to porosities, it does seem to be a logical step to do this and so derive a porosity/depth relation which might be useful in regional reconnaissance.

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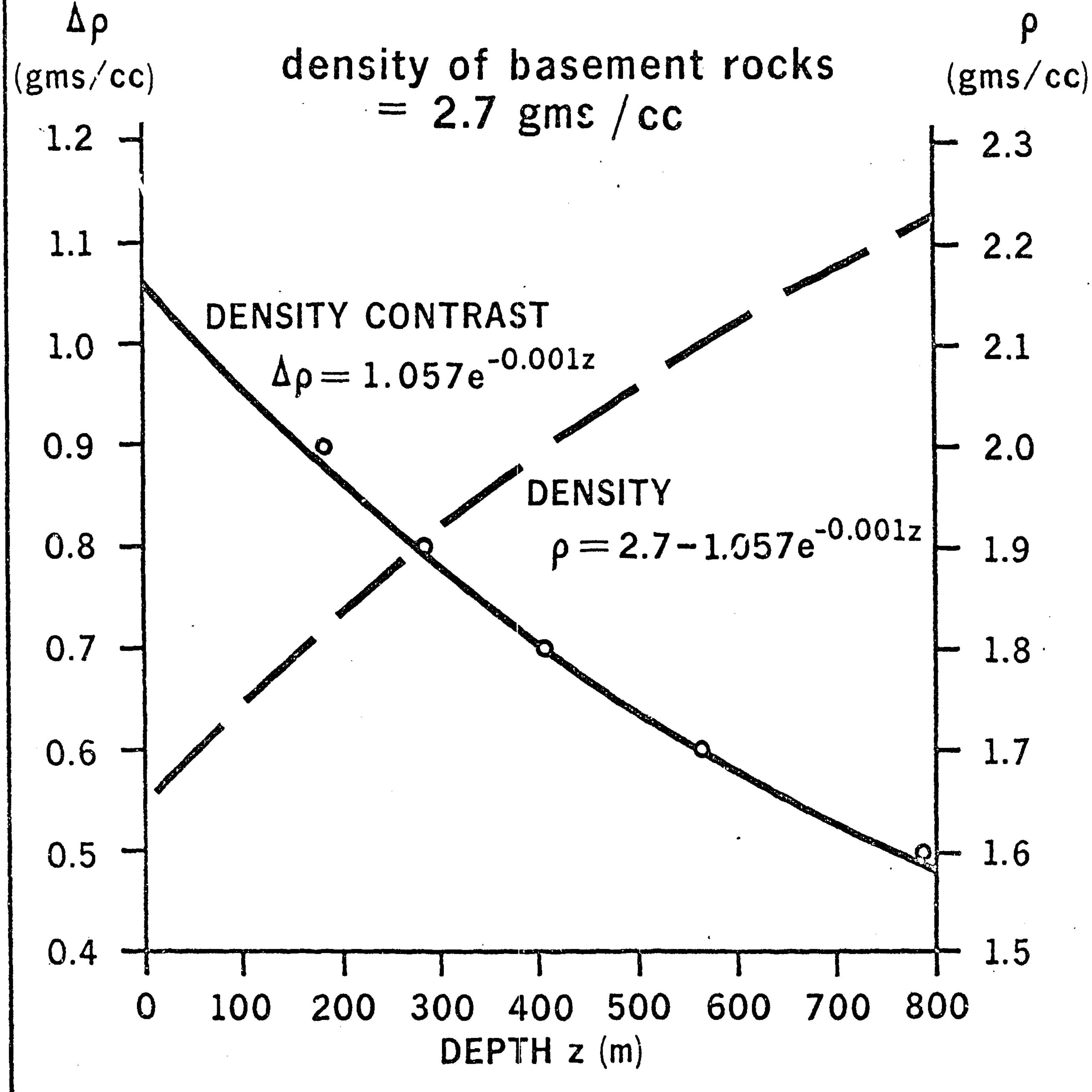

FIG.25

	DEPARTMENT OF MINES–SOUTH AUSTRALIA	SCALE
COMPILED: R G N.	GEOPHYSICAL METHODS IN HYDROGEOLOGY DURKIN TROUGH DENSITY–DEPTH RELATIONSHIPS	DATE: OCTOBER '76
DRN. / CKD.		PLAN NUMBER S12431
GEOPHYSICAL SERVICES		

DISCUSSION ON R.G. NELSON & B.E. MILTON'S paper

E.J. Polak (BMR)

What type of shooting did you use for your transverse velocity recording?

R.G. Nelson

We aligned the geophones perpendicular to the spread and the source was a steel stake driven into the ground which we hit in a direction across the spread. We recorded recognisable refractions.

E.J. Polak (BMR)

We have done a considerable number of this type of recording. We used a source consisting of a buried metal pipe closed at one end. A shot was fired in the pipe and the recoil at right angle to the spread produced a transverse wave. The spread consisted of horizontal geophones and we obtained penetration of 15 metres on two locations. On the Cluny dam site in Tasmania, where sandstone is located under shallow overburden, we obtained very good recordings of transverse waves. However when we proceeded to an area where the overburden was thicker and alluvium was present no transverse waves were recorded. For this reason I am quite surprised by your results, by both the velocities you mentioned and the penetration.

R.G. Nelson

We have found that we get generally better results by concentrating on recording second arrivals on vertical geophones, one arrival is the converted wave. From these velocities we determine the Poisson's ratio.

Mr Crawford (Darling Downs College of Advanced Education)

What do you expect to be the velocity of a rock beneath the water-table where the water occupies 2% by volume and the P wave velocity of the unsaturated rock is less than 5000 metres per second?

R.G. Nelson

I don't think the velocity would be distinguishable in this case.

Mr Crawford

I am talking about fractured basalt in this case.

R.G. Nelson

You would perhaps notice fracture zones in basalt where the fractures reduced the velocity of the basalt. Someone did do an experiment using microscope glass slides, the glass itself had a velocity of about 18 000 feet per second, 50 slides were put together and the velocity measured across the slides pressed together was of the order of 1650 feet per second. The velocity rapidly approached that of the velocity of glass, however, when these slides were saturated, and also the velocity approached that of the glass when only 2 slides were used.

GEOPHYSICS IN GROUNDWATER EXPLORATION - THE ROLE OF CONSULTANTS

AUSTRALIAN GROUNDWATER CONSULTANTS PTY LTD

(This paper was prepared by Dr W. Morton, Mr S. Hancock, Dr F. Carosene, and Mr I. Rowan, and was delivered by Mr S. Hancock)

1. INTRODUCTION

In a press article in 1970, an eminent professor wrote about the need to develop nuclear desalination plants in Australia because "... the groundwater resources of Australia are fully known and no new discoveries can be expected". Since this press article, my Company has successfully completed over 200 groundwater projects, many in remote and previously unknown areas; this work includes the installation of 10 major wellfields yielding a total in excess of 220 megalitres/day.

Geophysics played a significant part in the location and successful completion of these works at a total cost many times less than the alternative surface water scheme.

The Consultant's need for geophysics is probably greater than that for other people. Divine geological knowledge is freely available and freely given, so in areas where water is easy to locate by geological methods alone, the Consultant's expertise is not utilised: such areas presumably constitute our known groundwater resources.

The Consultant is generally called in after simple geological techniques have failed or where geological guides are absent. He is then faced with a problem of unknown dimensions.

To achieve results in groundwater exploration, it is necessary to fully utilise every tool available. It is necessary to realise the limitations of each tool used separately to know the value of combining several limited tools.

2. EXPLORATION TOOLS

- Archive studies,
- Hydrology,
- Geology,
- Geophysics,
- Drilling, and
- Hydraulic exploration.

Archive studies covers a total literature search and analysis, and includes a study of existing bore records. The results of this work must be treated with caution since it is generally a survey of pre-conceived opinions. Bore records should be assessed with reference to the purpose of the drilling, the efficiency of the structure, and the limitations of equipment used and the driller. I have seen large areas written-off on the basis of bore records only; these same areas now support wellfields supplying 30 megalitres/day.

Hydrology studies are essential. Adequate recharge potential must be available to support the required yield. Arid zones should not be analysed on annual rainfall figures; long-term-frequency storms can provide a high percentage recharge and support significant basin yields.

Geology and Geophysics are basically remote-sensing tools utilised to assess the physical parameters and boundaries of a groundwater reservoir. The two tools are necessarily complementary. An apparently uniform geological formation may show geophysical variations related only to hydraulic factors. A geophysical 'formation' may be an average of several geological formations. A regional survey must utilise both tools to fully understand the physical model.

Drilling and Hydraulic Exploration are the most expensive tools available. They should therefore be used in the most efficient way possible after all other tools have been properly utilised. Drilling targets must be defined, otherwise you will always be praying that the next hole will provide all your answers. Hydraulic exploration may tell you that you are in the wrong area only if the area tested is hydraulically connected to a better area.

3. EXPLORATION PHILOSOPHY

The most expensive and critical stage of any exploration program is drilling and hydraulic assessment. It is important therefore that this stage be planned to produce the maximum useful information. Wildcat drilling is expensive and can lead to erroneous conclusions. The general practice of a Consultant is to employ a staged approach to any groundwater project. Depending on the job, several stages may be combined, but individually, they consist of the following:

- Office assessment,
- Reconnaissance survey,
- Preliminary investigation (geology-geophysics, etc.)
- Drilling investigation and hydraulic exploration,
- Hydraulic evaluation,
- Wellfield design, construction and testing, and
- Management program.

After each stage, the chances of success and a cost estimate of the total program are reviewed. This enables the client to weigh his expenditure and risk factors.

A reconnaissance survey is necessary to identify the exploration problems and determine the best combination of exploration tools to achieve the objectives within an economic budget. This initial survey must be carried out by an experienced groundwater hydrologist who appreciates the use and limitations of all the exploration tools. He must prepare an investigation program with specific objectives in mind.

If geophysics is necessary, then the targets must be defined. Unless the geophysicist is also an experienced groundwater hydrologist, it is no good telling him just to go out and geophysically explore an area; you will end up with a mass of complex physical data, more problems than you started with, and a hefty invoice to pay.

The same principle applies to the drilling program.

The preliminary investigation stage is where geophysics should be used to best advantage. In a small project, geophysics can be used to pinpoint the bore site. In a large project, geophysics can be used to give continuous cross-sectional profiles to provide a regional understanding of complex geology. A minimal number of drilling targets can then be selected to test the best potential underground reservoirs, or anomalous geophysical zones. The data obtained from such drilling can be confidently extrapolated to geophysically similar areas and enable the construction of a complete regional picture of the groundwater basin.

The major use of geophysics in groundwater exploration from the Consultant's viewpoint is therefore as follows:

(i) to provide a regional three-dimensional physical model of the groundwater basin,

(ii) to provide a regional picture of groundwater salinities or permeability, and

(iii) to reduce the area available for siting a production or test bore.

It is fully realised that geophysics does not provide all the answers and does not itself locate a groundwater body, except in special cases of well known areas. Geophysics is used purely as a relatively cheap tool to provide additional physical data in order to better understand the groundwater basin and to reduce the costs of exploration drilling.

4. GEOPHYSICAL METHODS - USES AND LIMITATIONS

The various geophysical methods used commonly in groundwater exploration programs are fairly well known and include:

- Seismic
- Electrical Resistivity,
- Magnetics, and
- Gravity.

Also a variety of down-hole techniques, commonest amongst which are:

- spontaneous potential,
- resistivity,
- various radiation logs,
- thermal logs, and
- velocity surveys.

In the time available, it is quite impracticable to cover these with anything but brief comment.

4.1 Seismic

Seismic refraction and reflection have great value as basic geological measuring tools, for locating and sorting out structure, filled valley profiles, buried karst features, etc. They can also be of value when interpreted in combination with the results of other techniques. The major limitations of the technique are:

(i) it has limited application except in sedimentary environments,
(ii) it has no hydrological or hydrochemical value, and
(iii) it is the most expensive of all the techniques currently in use.

Our Company has only used seismic reflection where it has been available from earlier petroleum exploration programs. This particular form is simply too expensive for normal groundwater applications.

4.2. Electrical resistivity

This technique is certainly the most widely used technique, combining as it does the ability to be interpreted in a variety of ways in a variety of environments. It is a very powerful tool for use in bore siting, regional salinity assessments, etc. Its major limitation is that it requires skill, understanding and experience in:

- selecting the particular method to suit a particular problem,
- the electrode configuration to achieve a given result from the selected method, and
- the right equipment to give real results in a particular environment.

Finally, it requires an equal measure of skill, understanding, and experience to interpret the data correctly, because the data obtained is not necessarily discriminatory or specific against a variety of hydrological conditions.

My Company has used nearly every resistivity technique in the books, and maintains five resistivity units of differing powers, resolutions, and characteristics in order to cover the variety of conditions our work brings us in contact with. Normally at the start of every geophysical study, preliminary traverses and depth probes are carried out to "tune" our techniques and to select and adjust our equipment to give the best results. This is an essential preliminary operation. In some circumstances, we may use several techniques or electrode configurations over the one area to obtain resolution of the factors in which we are interested.

4.3. Magnetics

The magnetic method is the cheapest form of geophysics and has been found to be valuable both in broad-scale regional surveys and in detailed surveys. It suffers from the limitations of most geophysical methods, in that the data does not give specific results equatable to specific situations and is not hydrologically sensitive. It can be a useful tool in filling in form lines for structure where other exploration has given points of reference, and of course, in distinguishing between magnetically susceptible environments or concentrations and others.

Essentially, it is a good back-up geological tool, but it is not a prime hydrogeological tool. Its availability over broad areas as a result of airborne studies does, however, result in its being used as an input in initial studies based on archival information.

4.4. Gravity

Gravity surveys fall into much the same category as magnetic surveys, in that they are commonly available arising from regional surveys carried out by the Commonwealth and others. In specific environments such as deep buried valleys, and in volcanic regions, they can be very valuable as a specific tool, but they are seldom carried out by my Company.

5. SUMMARY

Consultants in hydrogeology are in all stages of their work constrained by economics - the need to be profitable and the need to keep within budgetary limits. As a result, research and experimentation are necessarily limited.

A further constraint is time - the need to complete a certain program and achieve answers within a certain period of time. As a result, the tools most commonly used are those which are rapid, positive, and economic. In Table 1, we give a comparison of costs between various methods. These need to be compared with drilling costs which for say a 100-ft profile, using auger drilling, would not be less than $300/1000ft spacing, with no charges included for casing, moving, or any other item.

We believe the best method of demonstrating the application of the philosophy and economics of geophysics as used by Consultants, is by presenting case histories. We present two - the first, the application on a large-scale operation and the second, a small-scale operation.

CASE HISTORY NO. 1 - TOWNSVILLE AREA, NORTH QUEENSLAND

The results of a reconnaissance survey of the Townsville area, carried out by the Consultants in 1970, indicated that it should be possible to obtain the required 5 million gallons/day for a proposed nickel treatment plant from the coastal plains.

Although little drill-hole information was available, it was thought that the plains would consist of colluvial and alluvial deposits derived from the adjacent ranges. If these sediments were sufficiently permeable and if there was sufficient saturated thickness, then it would be expected that recharge to the sediments and water stored within the sediments would be sufficient to enable a reliable wellfield to be established.

As a result, reconnaissance, seismic and resistivity traverses were carried out over three selected areas, in order to:

(i) determine the thickness and nature of the sediments,
(ii) detect any variations in water quality, especially near the coast,
(iii) gain a better overall geologic and hydrogeologic appreciation of the area, and
(iv) select sites for test drilling (if warranted).

In addition to the geophysical survey, a census of all existing bores was carried out.

The first stage consisted of surveying lines 4, 7, 8, and 9 (Fig. 1). The seismic geophone spacing used was 100 ft; resistivity traversing was carried out at 100-ft intervals with a current electrode spacing of 3300 ft. Depth probing was carried out at selected points.

The results of this survey showed:

(i) a generally undulating bedrock topography with depths to 180 ft,
(ii) sediments of varying resistivities,

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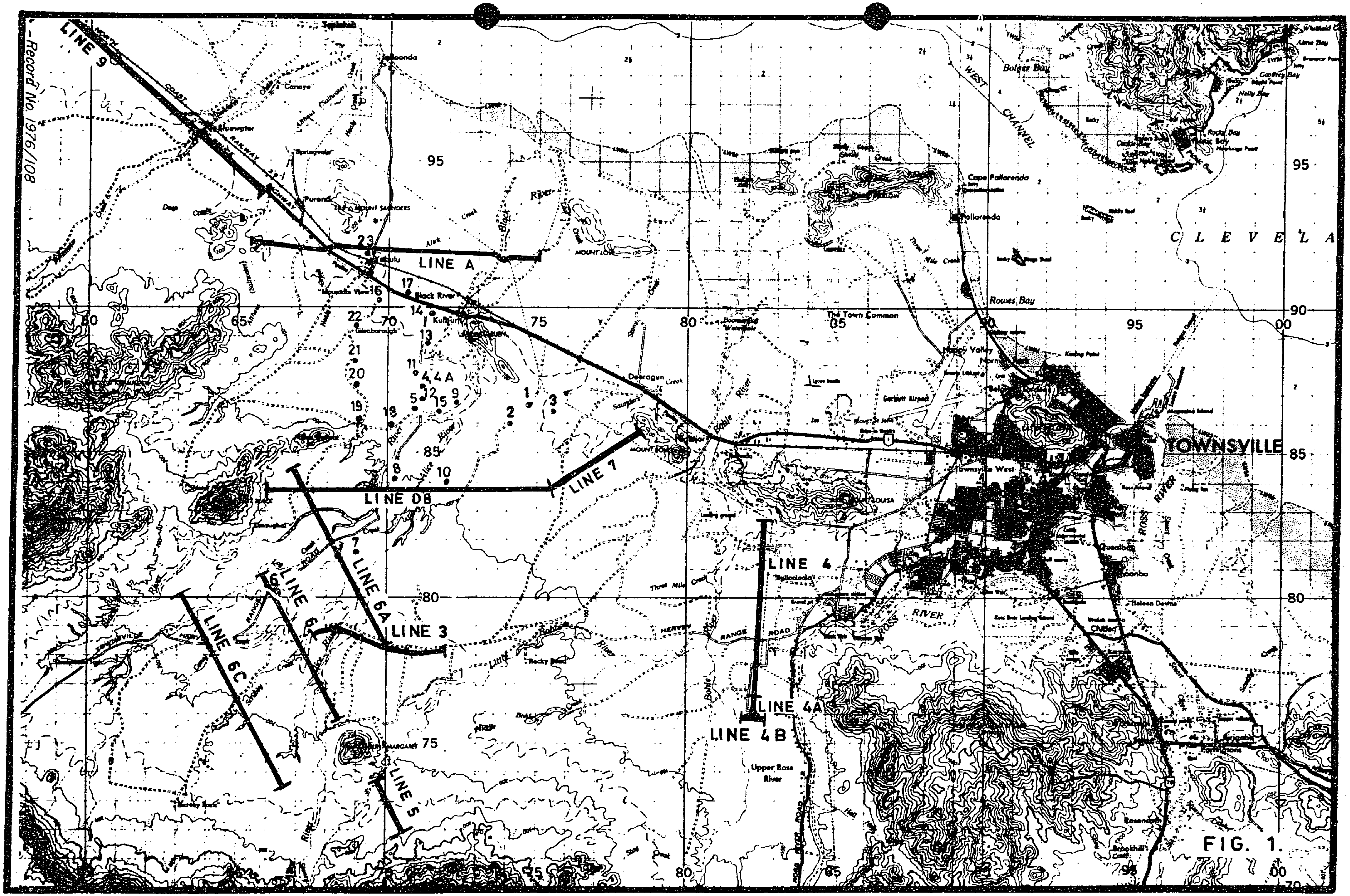


FIG. 1.

(iii) the possibility (in some areas) of fractured bedrock,
(iv) no evidence (except near the coastline) of saline groundwater, and
(v) a high groundwater gradient towards the coast, indicating a possible substantial underflow.

The vertical section can be summarised as:

Interpretation	Seismic velocities	Resistivities
Near-surface dry sediments to 30 ft	1800-2000 ft/sec	6-350 ohm-m
Saturated sediments to 180 ft	4500-7000 ft/sec	9-35 ohm-m
Bedrock	15,000 ft/sec	variable but 100 ohm-m

The exception to the above was on Line 9 where the saturated layer, although having similar resistivities to elsewhere, had a higher seismic velocity of 7000-8000 ft/sec.

These results were considered encouraging and it was decided to test drill. Line 8 was selected as having the greatest potential (Fig.2) and bore TTW1 was drilled.

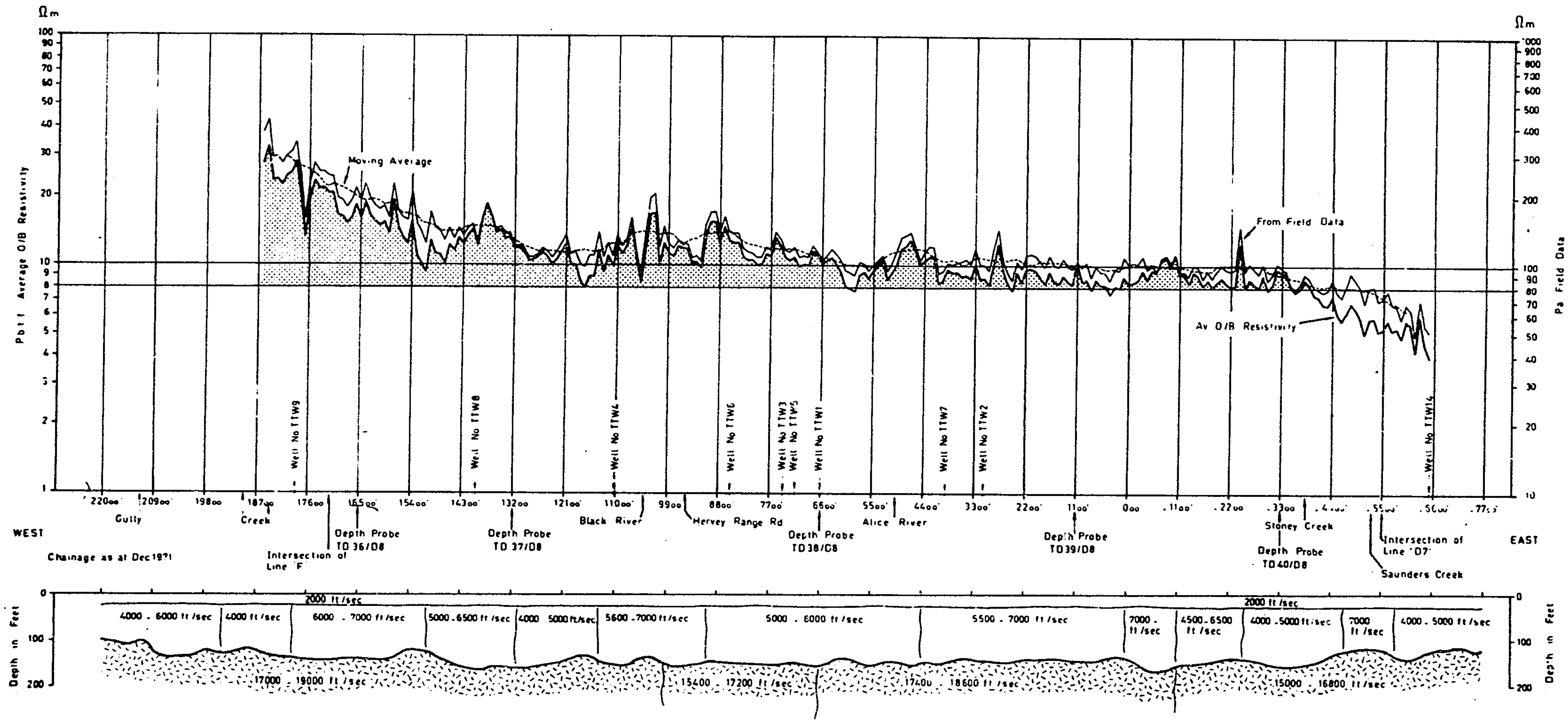
This bore intersected:

0 - 170 ft	-	alluvium, with several gravel/boulder aquifers
170 - 345 ft	-	granite

As a result of this, the test drilling was extended along this line to test the various zones revealed by the geophysical results. Production bores were constructed and pump-tested to obtain aquifer characteristics.

Further geophysical traverses were completed to:

(i) define the extent of the most favourable area,
(ii) select further production and test hole sites, and
(iii) obtain more general information to enable subsequent calculations to be made with greater reliability.


Moving Average
From Field Data
Av O/B Resistivity
Pb t t Average O/B Resistivity
Pa Field Data
WEST
EAST
Chainage as at Dec 1971
Gully
Creek
Intersection of Line 'F'
Depth Probe TD 36/D8
Depth Probe TD 37/D8
Black River
Hervey Range Rd
Depth Probe TD 38/D8
Alice River
Depth Probe TD 39/D8
Stoney Creek
Depth Probe TD 40/D8
Intersection of Line 'D7'
Saunders Creek
Well No TTW9
Well No TTW8
Well No TTW4
Well No TTW6
Well No TTW3
Well No TTW5
Well No TTW1
Well No TTW7
Well No TTW2
Well No TTW14
Depth in Feet
2000 ft/sec
4000 - 6000 ft/sec
4000 ft/sec
6000 - 7000 ft/sec
5000 - 6500 ft/sec
4000 - 5000 ft/sec
5600 - 7000 ft/sec
5000 - 6000 ft/sec
5500 - 7000 ft/sec
7000 - ft/sec
4500 - 6500 ft/sec
4000 - 5000 ft/sec
7000 ft/sec
4000 - 5000 ft/sec
17000 - 19000 ft/sec
15400 - 17200 ft/sec
17400 - 18600 ft/sec
15000 - 16800 ft/sec

LINE D8

FIG. 2

The picture which emerged is shown in the following figures:

Figure 3 - is a seismic bedrock contour plan (alluvial isopachs)

Figure 4 - is a contour plan of apparent resistivities from the traversing

Figure 5 - is a combined seismic/resistivity profile along the northernmost traverse (traverse A).

As a result of this additional work and the pump test results, a wellfield was established capable of supplying 5 million gallons/day (later increased to 7 million gallons/day). The areal extent of the final wellfield is shown on Figure 4.

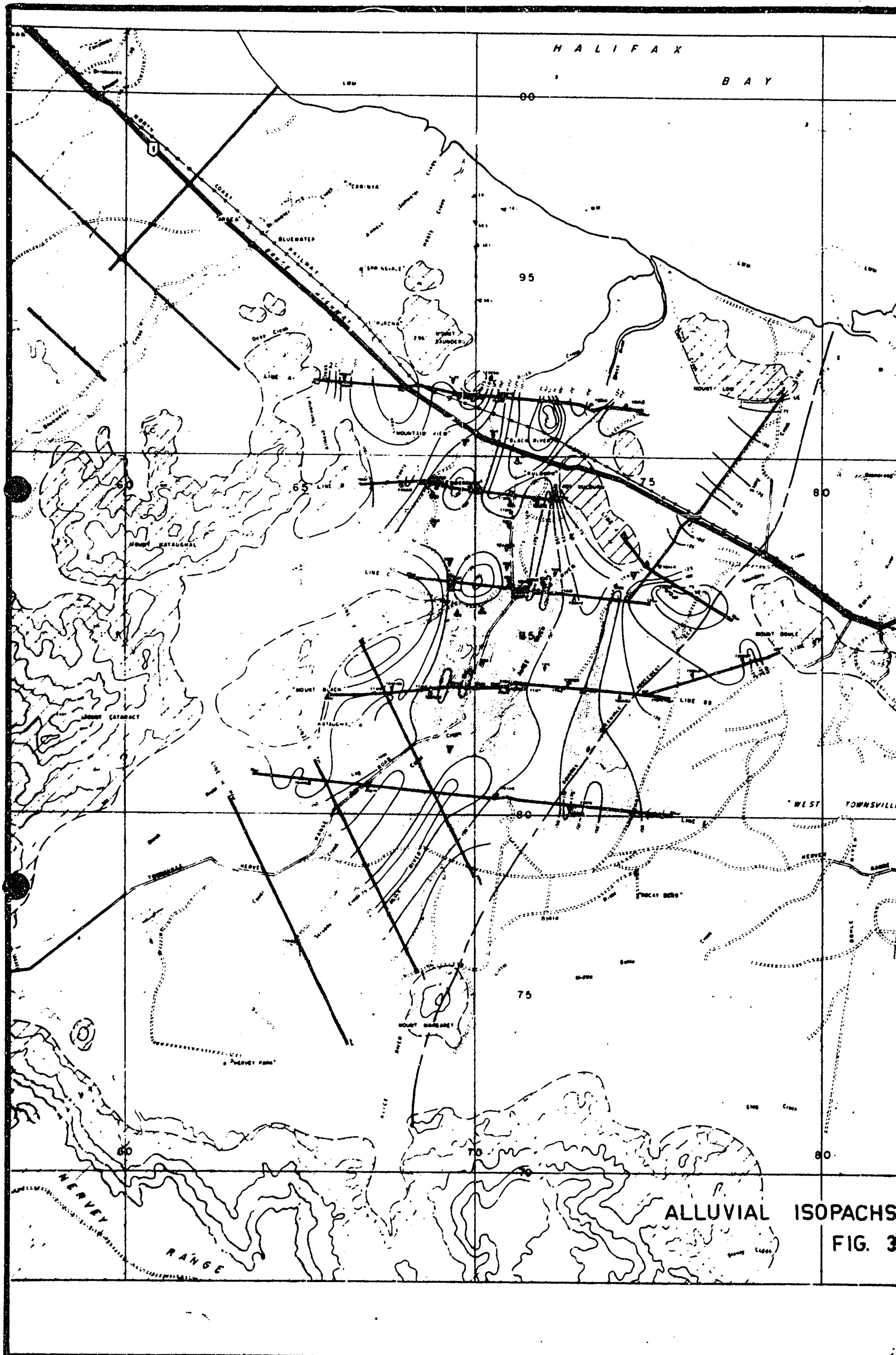
1. BLUEWATER BASIN

As part of the investigation of the Townsville plains area, seismic and resistivity traverses were carried out over the Bluewater Creek area, west of the Black River/Alice River area (Line 9). The Bluewater area is situated at the base of the Paluma Range, which consists of volcanic rocks.

The resistivities of the overburden as measured from depth probing proved similar to those in the Black River area. The seismic results showed similar depths to bedrock; however, the overburden velocity was greater and averaged 7000-8000 ft/sec (cf. 4500-7000 ft/sec). Also, the seismic results did indicate the presence of thin discontinuous high-velocity layers within the overburden sequence.

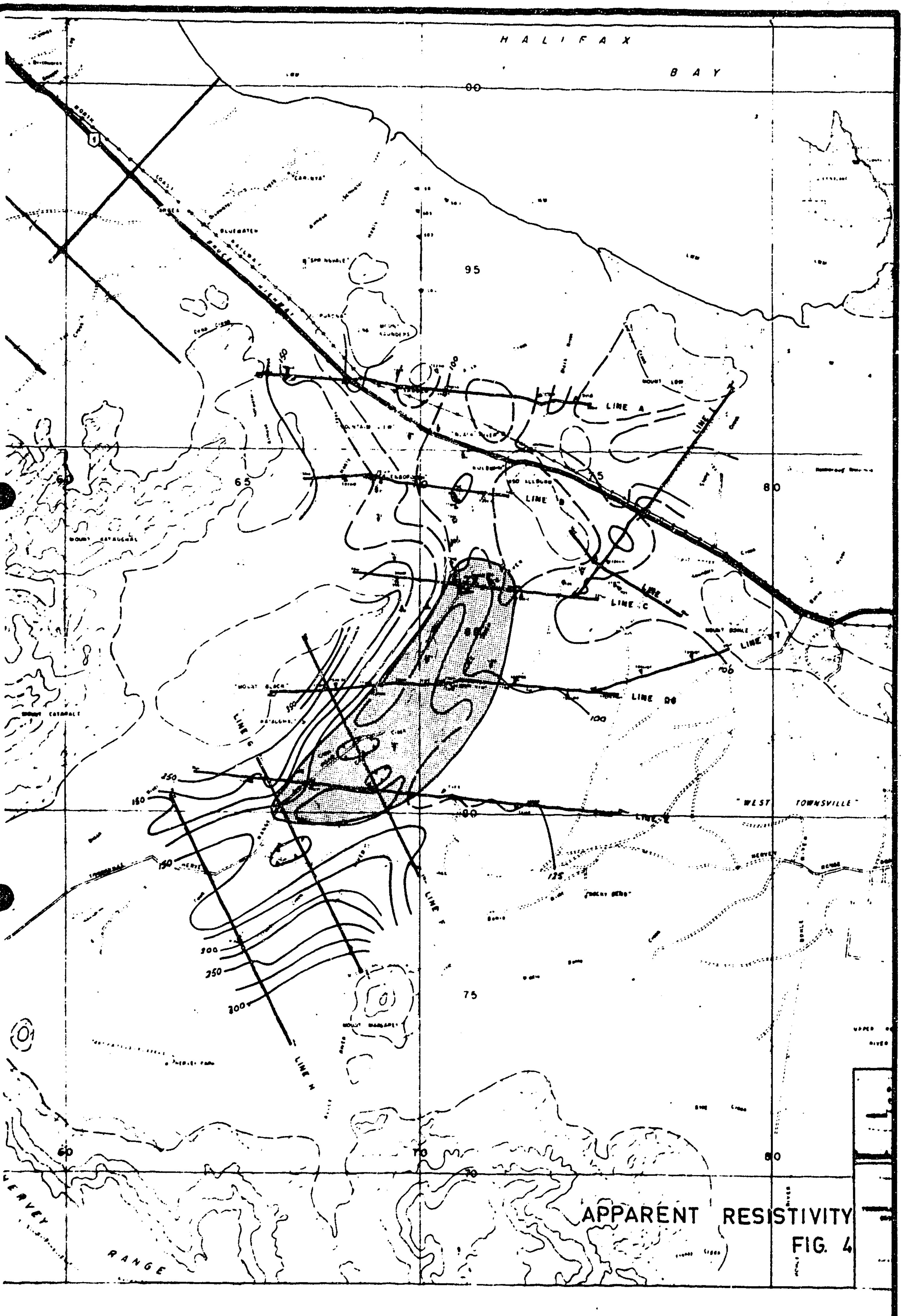
Test holes were drilled in this area and revealed the overburden to consist of poorly sorted, clayey, colluvial deposits with lateritic bands. Yields of the test bores were low and salinities generally higher than in the Black River area.

Although the seismic results did indicate a higher overburden velocity, the resistivity results were similar to those in a nearby productive area. It is apparent therefore that the use of absolute values for comparing areas can be misleading, and that the geophysical results in a particular area should be 'calibrated' against geologic information from that particular area.

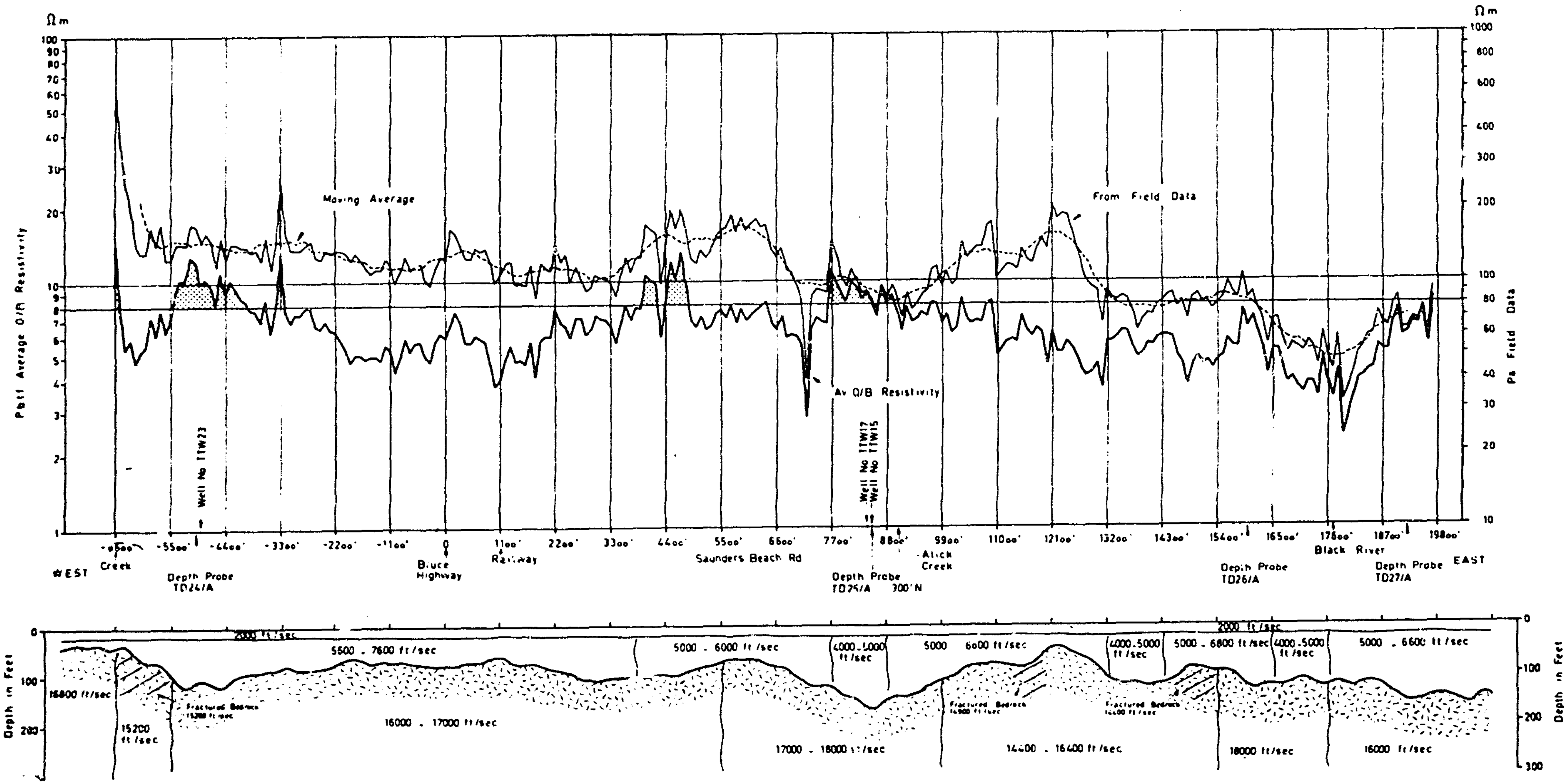


ALLUVIAL ISOPACHS

FIG. 3



APPARENT RESISTIVITY
FIG. 4


Ωm
Ωm
Pbtf Average O/B Resistivity
Pa Field Data
Moving Average
From Field Data
Av O/B Resistivity
Well No TTW23
Well No TTW17
Well No TTW15
WEST
Creek
Depth Probe
TD24/A
Bruce
Highway
Railway
Saunders Beach Rd
Depth Probe
TD25/A 300'N
Alick
Creek
Depth Probe
TD26/A
Black River
Depth Probe
TD27/A
EAST
Depth in Feet
Depth in Feet
2000 ft/sec
5600 - 7600 ft/sec
5000 - 6000 ft/sec
5000
6000 ft/sec
5000 - 6800 ft/sec
5000 - 6600 ft/sec
16800 ft/sec
15200
ft/sec
Fractured Bedrock
16000 - 17000 ft/sec
17000 - 18000 ft/sec
14400 - 16400 ft/sec
18000 ft/sec
16000 ft/sec

LINE A

FIG. 5

2. GROUNDWATER INTRUSION

As part of the long-term monitoring of the wellfield performance and its effects, it was necessary to determine the presence of the freshwater/sea-water interface in order to select the optimum positions for the establishment of observation bores.

A series of electrical depth probes was carried out between the plant site and the shore. The results of these are shown in Figure 6 and show clearly the effects of salt water intrusion which can be expected near the coast.

(a) The layer of fresh water above the saline and brackish zones in the near shore dune system. This layer is used extensively by small communities along the coast of Australia. Electrical geophysical methods provide a quick, cheap method of determining the presence and the vertical and lateral extent of such a layer.

(b) The resistivity of the bulk of the saturated alluvium behind the saline interface is approximately 10 ohm-m. This value is lower than the resistivity of the saturated alluvium in the wellfield area (10-35 ohm-m); however, this can be explained by:

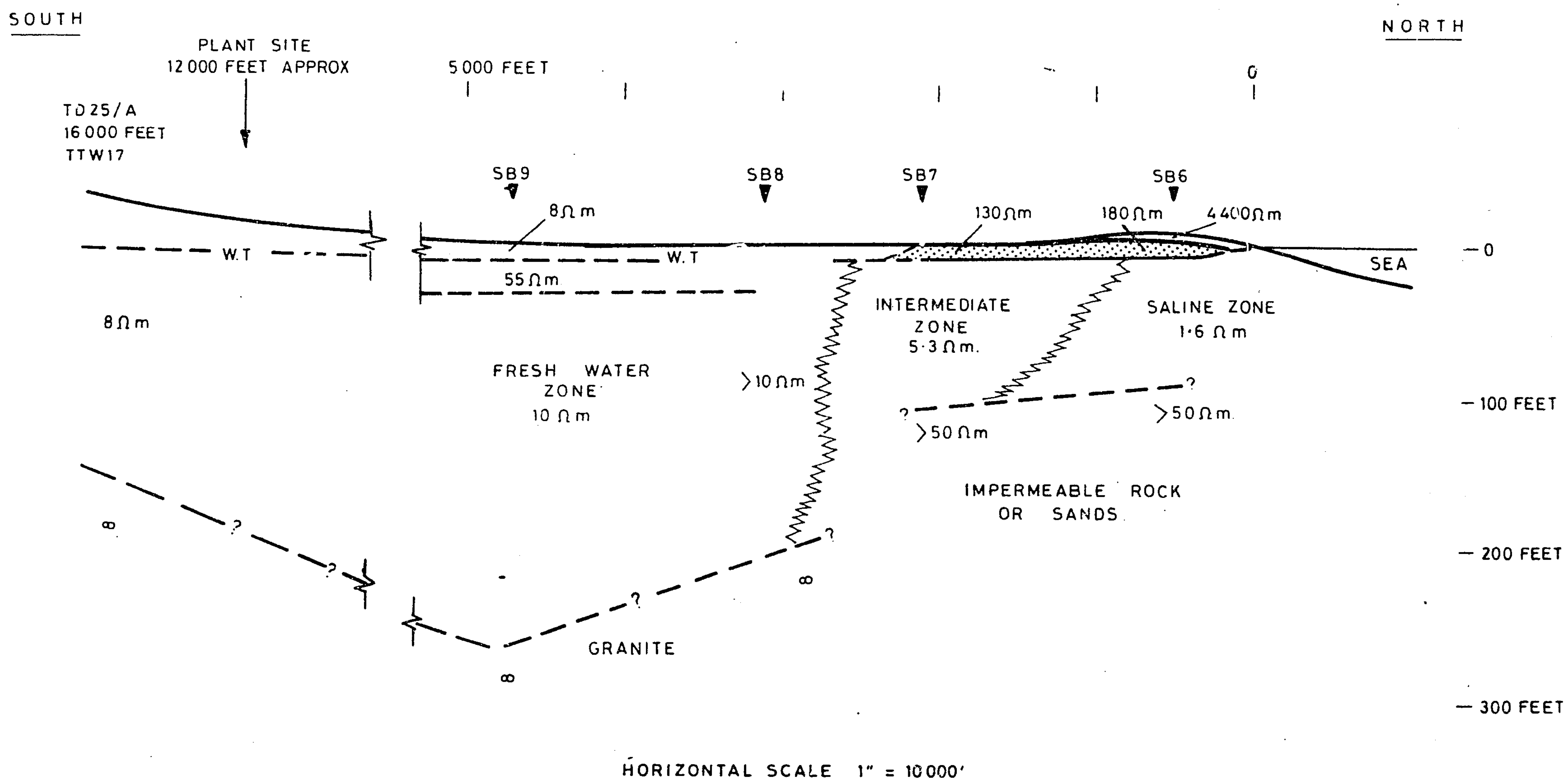
  (i) a generally higher clay content, and

  (ii) a generally higher T.D.S. content in the groundwater (400 ppm vs. 250 ppm).

As a result of these results presented and of other electrical work in the area, it was established that the effects of sea water are limited to within 2500 ft of the shore line and to shallow effects near the tidal estuaries. Seven observation holes have been drilled to monitor changes in groundwater salinity between the plant site and the ocean.

3. COST COMPARISONS

The final geologic interpretation of the wellfield area is that the sedimentation in the area is of a random nature. The nature of the sediments is representative of a series of coalescing colluvial fans within



INTERPRETED GEOELECTRIC SECTION ALONG DEPTH PROBES SB6 TO TD25/A.

FIG. 6

an ancient valley. Superimposed within this system are alluvial fan and meandering channel deposits - the width of the channel deposits varies from 100 to possibly 500 ft. It is the alluvial deposits which have the higher transmissivities and are the target areas for production hole sites. The wellfield itself occupies an area about 5000 ft wide by 6 miles long.

As a result of the original reconnaissance survey, 92400 ft of geophysical traversing was completed in three separate areas.

For the sake of comparison, it could be said that the known status of the aquifer graduated from 'inferred' to 'probable', after the completion of this geophysical work and the drilling of 7 test holes on Line 8.

Contract costs to this stage would have been approximately:

Geophysics	
Seismic, electrical traversing, and depth probing - 84 spreads @ $200 each	16,800
Drilling	
7 test holes to 150 ft average @ $1200 each	8,400
Total (excluding supervision and expenses)	$ 25,200

Assuming that geophysics had not been used and test drilling was the only exploration tool used, then for the costs as given above, a total of 21 holes could have been drilled. If we required information over the proposed 92400 ft of traverses, this would be equivalent to one hole every 4400 ft of traverse.

Given the information that we now know about the wellfield, then it is probable that, using a spacing of 4400 ft for test drilling, only one hole would have been drilled in the wellfield area. The chances that this hole would intersect one of the alluvial channels would be remote.

4. SUMMARY

(i) Hydrogeological reconnaissance surveying had indicated the possibility of establishing a wellfield provided certain conditions prevailed. Certain areas were selected for testing.

(ii) Geophysics indicated favourable conditions. A comparatively small area was selected for test drilling.

(iii) Test drilling and subsequence test pumping proved suitable.

(iv) Further geophysics to accurately define the extent of the most favourable area, to select production sites, and to generally increase knowledge of the area to enable a more comprehensive model to be built than would otherwise have been possible.

(v) Production hole drilling and testing.

CASE HISTORY NO. 2 - NORTHERN PLAINS, VICTORIA

1. BACKGROUND

In the valleys of the Murray, Goulburn, and Campaspe Rivers in northern Victoria, horticulture has been an important and valuable industry for over 100 years. This industry has grown and expanded on the basis of a surface irrigation scheme covering large areas of the plains. In particular, the peach, pear, and apricot orchardists have been affected, over the last 30 years at least, by rising water-tables and with them rising salt. This has caused a decline in the areas capable of being used for this purpose and, particularly since 1974 which was a very wet year, the situation has become critical.

Government investigations have been mounted in the area, but with the scale of the problem, the slow speed of operations, and the local nature of the effects, a group of orchardists requested our assistance in establishing local schemes capable of producing rapid results.

2. PROBLEM

Initial studies of the records, and contact with Governmental authorities, indicated that the rise in water-table was due, in the area in which we were working at least, to pressure from sand aquifers interbedded and underlying the surface deposits. These sands occur as narrow, buried remnants of prior streams, the courses of which were sometimes evident from detailed geomorphic studies at the surface, but more often were completely hidden and quite random in their occurrence, particularly where they occurred at depth.

The shallow deposits themselves are deposited, in turn, in an older alluvial sequence which of itself contains sand beds, but which contains very saline water (8000-15,000 mg/l).

Thus, the problem resolved itself into locating sites for pumping at which:

(i) highly permeable aquifers could be intersected at depth,
(ii) aquifers contained water of a salinity that could be accepted into the irrigation drains (not more than 1500 mg/l initially),
(iii) close to the most critically affected area,
(iv) reasonably close to power and discharge points, and
(v) the system would not unduly disrupt the operation of the orchard.

3. APPROACH

A straight grid drilling approach was considered but was rejected on the basis of the extremely variable nature of the sequence and the lack of control on salinity. Also, it was too expensive.

Electrical resistivity was then considered and was tested and experimented with using different techniques and different instruments over sections that had been drilled and logged in detail by the State Rivers and Water Supply Commission.

Shallow, highly saline waters (up to 40,000 mg/l) were considered likely to "shunt" surface currents and cloud the readings from underlying layers. For this reason, two relatively powerful units were tried in order to assess their suitability. After completion of these tests, work at the first property began.

On each property a plan of the property with roads, salt-affected areas, power and drainage was prepared. On the first property, both electrical resistivity traversing and depth probing were carried out. Based on the apparent resistivity values determined, auger drilling was then carried out to obtain samples of the sequence and the water and to permit simple pumping tests to be carried out.

4. RESULTS

In the above manner, 10 properties were studied and 6 successful pumping systems were installed. The locating of these sites required an average of 2.5 days' resistivity depth probing work at each property.

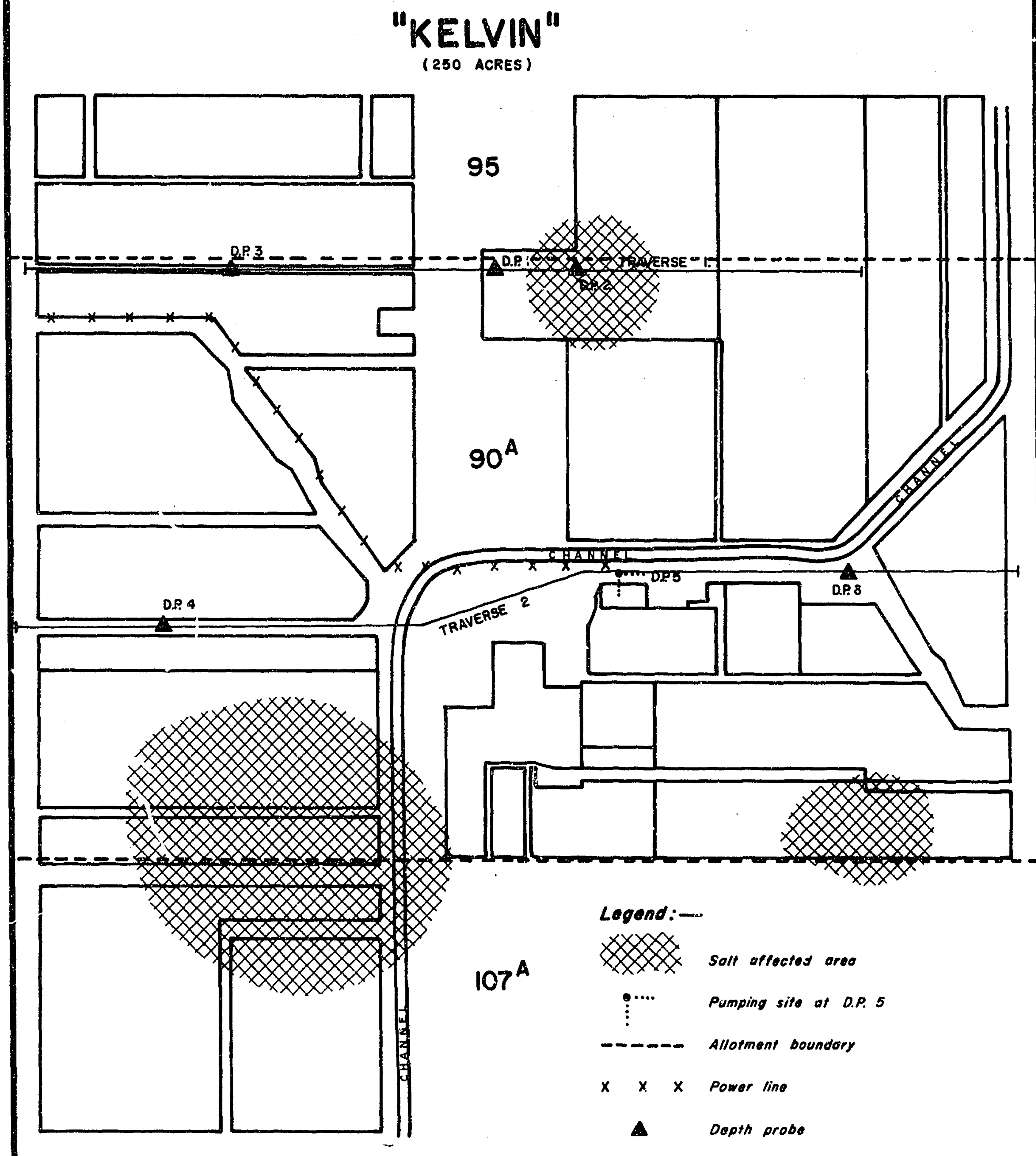
The resistivity traversing was found to give inconsistent results, and only depth probing, using both Schlumberger and Wenner configurations, was used thereafter. After a number of bores had been drilled to test the geophysical results, the following results were found to apply:

Apparent resistivity ohm-m	Lithology
4	Clays or sands saturated with saline water
4-14	Sands containing brackish waters or clays
14-20	Sands containing fresh water
20	Compacted interbedded clay and sand sequence

Clearly the results are not discriminating between lithology and salinity exclusively; however, they do permit the location and identification of sand aquifers containing water of salinities acceptable for disposal and at locations where effect, power and disposal criteria are, to some extent, optimised.

In general, depth probes were carried out at about 400 ft intervals, at locations which were based on an expanding grid relative to the problem area and the various necessary back-up facilities. After experience on several properties, test bores to locate the best site for the pumping systems became unnecessary. In some cases, however, test bores were still drilled and kept as deep observation bores.

The pumping systems were normally made up of two lines of spear points at right angles, spread at 10-m intervals and using about 12 spears. The average depth is 50-55 ft. The highest yield pumped was 4.9 Ml/d from one



KELVIN ORCHARD CO. PTY. LTD.

LOCALITY PLAN

PARISH OF TOOLAMBA

ALLOTMENT No. 90^{A}, 95, 107^{A}

by

Australian Groundwater Consultants Pty. Limited.

FIG. No. B 1

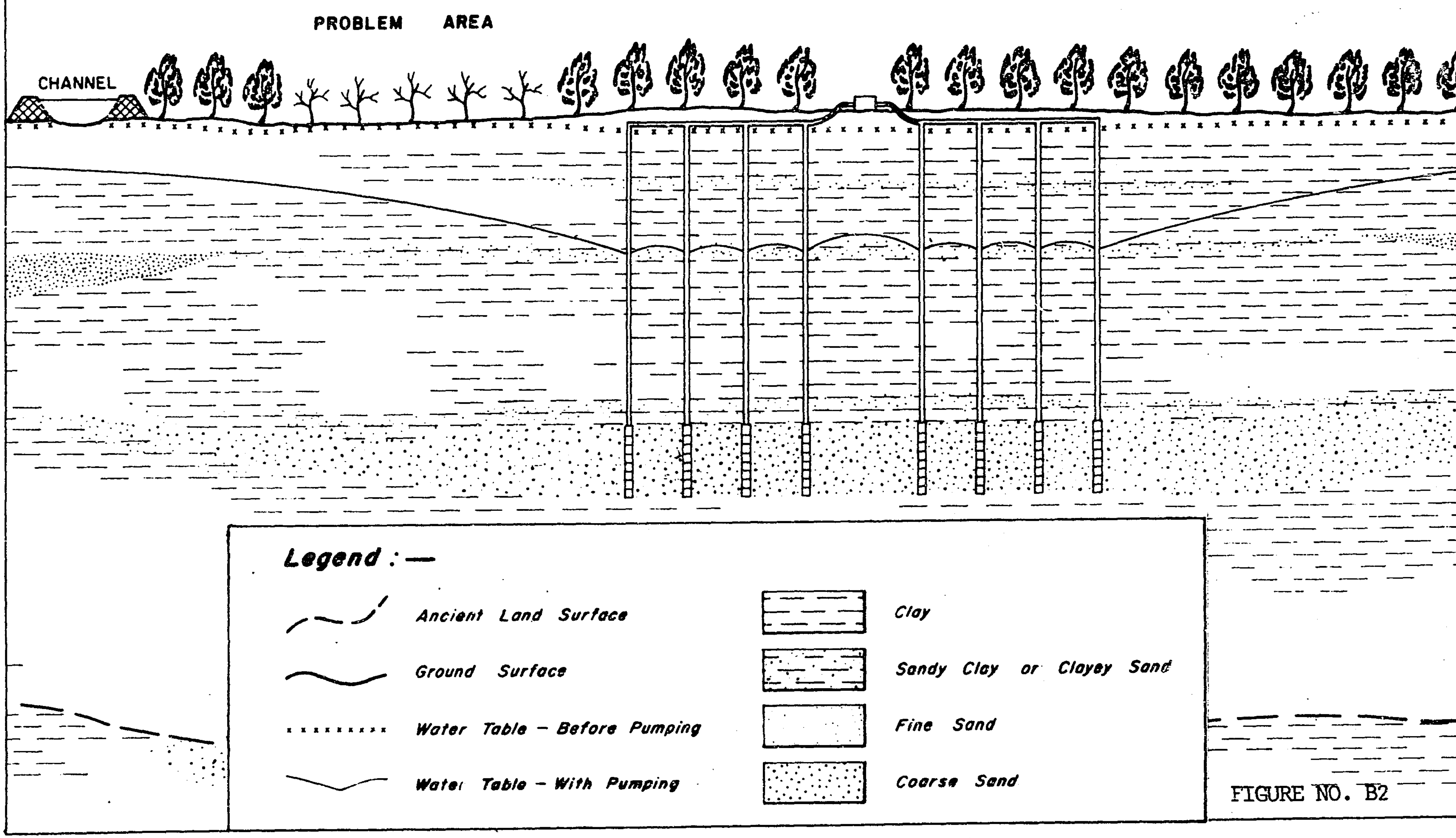

PROBLEM AREA
CHANNEL
Legend :—
Ancient Land Surface
Ground Surface
Water Table – Before Pumping
Water Table – With Pumping
Clay
Sandy Clay or Clayey Sand
Fine Sand
Coarse Sand

FIGURE NO. B2

TABLE 1 - COMPARISON OF GEOPHYSICAL COSTS (CONTRACT RATES)

	SEISMIC	$/day	RESISTIVITY	$/day	MAGNETICS	$/day	GRAVITY	$/day
PERSONNEL								
Geophysicist	(Computation)	160	(Computation)	160	(½ Computation)	80	(Computation)	160
Observer		100		100		100		100
Assistant(s)	(3)	75	(2)	50			Surveyor ½	75
							Chainman ½	40
VEHICLES								
$20.00/day	(2)	40	(1)	20	(1)	20	(1½)	30
EQUIPMENT	Recorder, etc	50		50		30		30
	Explosives	20						
	Film	20						
	Miscellaneous	20		20		20		20
ACCOMMODATION								
$20.00/day		100		80		30		60
INTERPRETATION & REPORT		180		180		180		180
TOTAL COST/FIELD DAY		765		660		460		695
DAILY COVERAGE								
(100ft readings)		4,000		7,000		10,000		6,000
$/100ft TRAVERSING		191.25		94.30		46.00		115.85

system, with the average being about 1.8 Ml/d. The only other comparable system put in by a Government authority based on drilling alone, pumps about 4.4 Ml/d from 25 spears and the salinity is about 2500 mg/l.

The salinity of water pumped from the systems installed in our program varies between 200 and 1200 mg/l after stability has been achieved and, on the largest property after two months' pumping, the piezometric water level had dropped over 4 m, one kilometre from the spear point system, and the water-table measured in overlying clays had fallen over 2 m.

5. CONCLUSION

The use of electrical resistivity both for locating initial sites inexpensively and for tracking sands to permit pumping system orientation, was most successful.

In addition, the results of the pumping and the resistivity values have shown that the shallow soils are not saturated with brines, but the brines occur in prismatic fractures in the clay overburden. This accounts for certain horticulture anomalies which had been observed by the orchardists.

A purist analysis of the resistivity data obtained would have been that the technique is incapable of distinguishing between clays and sands because of variations in contained water salinity. However, the pragmatic analysis has given the answer to a problem and other data of great significance in understanding and analysing the problem in this area.

DISCUSSION ON PAPER BY AUSTRALIAN GROUNDWATER CONSULTANTS PTY LTD

Mr Crawford (Darling Downs College of Advanced Education)

In your organisation where geophysics is done occasionally, how do you justify employment of a full-time geophysicist? Or do you take on geophysicists for part-time work?

S. Hancock

We employ three full-time geophysicists in our organisation and they would spend about 50% of their time employed in the planning, managing, and evaluation of geophysical programs. They spend the other 50% of their time in other areas of our consulting practice in which they have been trained and have gained experience. Here they are backed up by more senior staff, who are expert in these fields in the same way as the geophysicists are expert in their chosen field of specialisation.

In this way, we utilise their time fully, expand their training and experience, and improve their overall understanding of our field and of the role of geophysics therein.

So far as field crews are concerned, one of the ways in which we get around this problem is by having several trained people in our organisation who undertake a number of different tasks. For example, in Victoria, we have a pump test crew who are employed part-time on running pump tests and who include one of our draftsmen, who also is trained as a crew leader for geophysical surveys. On longer projects, e.g. Townsville and other projects in Western Australia, we actually employ people for the period of those projects, who have had experience on geophysical crews. Training time is generally very short, provided you have on site a geophysicist and crew leader who know what has to be done and how it should be done. Field hands are trained very quickly. In summary, both our geophysicists and technicians are employed on a variety of different jobs. It seems to be a mutually agreeable arrangement.

D.E. Leaman (Tasmaniam Department of Mines)

You mentioned in your paper a purist interpretation. Could you perhaps elaborate on this?

S. Hancock

In any exploration or testing program which obtains mathematical parameters for the earth, the interpretation involves four procedures to obtain a final answer which may or may not be correct. These are:

(i) A numerical interpretation to obtain the physical parameters. These may or may not be unique,

(ii) An explanation of the parameters in terms of the geology which may or may not be unique, depending on the extent of geological information,

(iii) Alteration and further refining of the interpretation in the light of new data, and finally

(iv) A re-evaluation of the whole program, which was carried out after the project is completed, to identify errors in planning and interpretation so as to avoid these in the future.

To return to a purist approach; too often geophysicists do not involve themselves in the data beyond stage (i); or they attempt to present the geophysical data as the answer itself, instead of working with the geologist to come up with the best and most valid interpretation possible at that time, relevant to his requirements, whatever they may be.

As I mentioned before, our geophysicists are very much part of the interpretative process which incorporates all the geological, hydrochemical, geophysical, and site condition data together, to get a practical answer, relevant to hydrogeology and the questions confronting us.

D.E. Leaman (Tasmanian Dept of Mines)

You used the term "properly interpreted" in your paper. This was probably covered in previous sessions, but what exactly do you mean by proper interpretation, say in resistivity, particularly in resistivity? For instance, do you have computational facilities in your offices, such as a medium-size computer?

S. Hancock

No, we do not have a computer in our office; however, we use computing facilities where necessary. These we use more commonly for seismic than for resistivity.

D.E. Leaman (Tasmanian Dept of Mines)

Perhaps if I could elaborate my question. People familiar with Merrick's paper realise that we had a very excellent exposition of the resistivity method and the refinements of the method as such, and also what I would call the very extreme end of the interpretative method, an end that very few people ever get to.

The discussion went as far as to discuss an inversion interpretation procedure which was a very good discussion in itself, but the question asked yesterday, was it all really worth it and you have touched on this aspect here, so I am really asking you how much validity do you place on resisitivity interpretation and how far do you take them at various stages, and why and how well do they compare in fact with the geological situation; are you for instance worried that the basement is interpreted at 25 m and is actually at 35 m, or are you interested more in a qualitative analysis, such as the shape of the curves? I realise I am asking a lot, but perhaps you could answer these points for me.

S. Hancock

Your comment is a valid one. The depth of interpretation that we would apply at any particular time, would depend on how much data we had and what our aims were. In answer to the accuracy of our determination of depth of bedrock, the answer is no, if we are trying to get a spread of information for instance across a small basin, but we do want to know, for instance, whether we are dealing with weathered bedrock or a cemented sediment. Furthermore, in areas where we have a lot of statistical background, or we think we have a lot of statistical background, we do try to sort this out and remove some of these local effects and see what our broader trends are. When I was talking about proper interpretation, one of the things I wanted to mention here was, it is important to realise there may be more than one interpretation - that you may not have a single answer to that one set of values - and if this is the situation, then this must be stated very clearly. The examples I can think of here for instance are, velocity inversion in seismic: where you can get a depth but there is something in your geology which tells you that you are getting a softer layer under a hard layer, then one needs to examine the geophysical seismic results more carefully. This is what I am getting at by proper interpretation. That is, getting to a point where you appreciate the limitations of your results and the range of interpretations. You are, in fact, selecting a particular interpretation which you think is the most probable. Now I must refer back to this factor that consultants must be always willing to change their interpretation, if it is shown at a later date that perhaps they had some of the assumptions initially wrong. As a project progresses, we get more data all the time, so we need to be evolving and upgrading our interpretation of the total data regularly.

The other point that you raised was about computer interpretations. This is quick and cheap, but it is not necessarily a good thing to do, unless in fact you are physically there, involved in the writing of the program and understanding the limitations of those programs and of your field data. You can lose touch with what your field data is showing and what problems there may be in the field data. Now our geophysicists are always in the field when our data is being run. When they have problems of data, or think they have problems of data, they will re-run certain sections. When they have areas and they are doing much of their interpretation in the field, particularly simple interpretation, they will go back and perhaps run a different technique back across the anomaly to see whether they can confirm the answer which they have got. I believe that geology and geophysics must be done in the field and not in the office; this is an important factor and this case history that we come to now is one for instance, where we did all the work at a office near the site.

E.J. Polak (BMR)

I think there is a collision course evident in your paper. You stated several times that you are using geophysics as a tool, but listening to your statements, you are using geophysicists as a tool. All the time you are talking of taking geophysicists to do this, etc., and so on. I use this only to illustrate the case, that in Australia, with engineering geologists and engineering geophysicists working on an engineering project and meeting with engineers, often the engineering geologists and geophysicists are treated as substandard people - in the sense that they are people on a project up to a certain point and then at some stage, they are forgotten and the final decision is the decision of the engineer. I could cite an example where over one million pounds sterling could have been saved if, in the final decision, the engineer had not forgottor about the existence of geophysics and geophysicists. There are, of course, several other cases where much money is involved. Following your paper carefully, I gained the impression that the geophysicist was the person to be used and later forgotton.

S. Hancock

If I could reply to that, Eddy, you should have started listening earlier than where I mentioned geophysics as a tool, because I said that in our own organisation we have overcome this problem and I wish to stress this. All consultants are going to have their areas of expertise. Mine is hydrology with a geological background. The geophysicist will have his area of expertise as geophysics, but he must also have an understanding of the engineering and geological aspects of the job, even as much as the engineer must have an understanding of the geophysics. Now I made a comment about involving our geophysicists in the developing concept of the overall environment in which we are working, and their input is interpreted in terms of "here are the results and we know this much about it". A round table discussion of all disciplines follows, and the end result which comes out is, in fact, a composite, not a result coming out of an engineer or out of a geologist. I am sorry if you have got the wrong impression about my statements of using geophysics as a tool and you see it as using geophysicists as a tool.

Again I stress that geophysicists must be involved in the overall aspects to the same extent that the engineers and geologists must be involved in the geophysics. You will find that the training of geophysicists, amongst other specialists, does tend to produce a person who thinks only as a geophysicist, or whatever; this is a poor basis. The geophysicist is a part of the total program of data gathering, and the project must have his input to the overall interpretation of all the data, including drilling data at a later stage. We should not lose sight of the fact, for instance, that the geophysicist should be looking at the bore logs and looking at down-hole geophysics and relating that back to what his surface measurements have shown. He then should state his opinion of what he feels is happening and then differences of opinion should be ironed out. I strongly believe that geophysicists have to be given a broader scope than just geophysics to work in, and I don't think we are on a collision course on that fact. I think that there is a basic division of specialisation at training time in the universities, and I think this is a great pity. I often wonder whether geophysicists should be given a major geological training and geologists be given a major geophysical training, but a lot of the new graduates we are getting into our organisation, tend to come with a very heavy physics background, and they understand their methods very well and the limitations of those methods, but they don't initially understand how they fall into the overall system of data gathering. It's the old thing - geophysics is not a panacea, a curer of all ills or a single tool. It is one of a number and the geophysicist needs to be involved in all of those tools, and understand where their data fits into that spectrum of the information obtained from the various different techniques.

E.J. Polak (BMR)

I agree with this point. I wish to correct another impression you gave concerning the division of scientists, engineers, and geologists. If you look into the training of engineering geophysicists in Australia, you will possibly find that 25% are engineers by training and probably it would be much better if this number was 50%.

S. Hancock

I think this is probably correct. I do believe that many of the other 75% are being kept in too narrow an alley, and this is something that really needs to be broken down.

Mr Crawford (Darling Downs CAE)

My comment is on the same subject. I think part of the problem is that the geophysicist, by his training, sees his responsibility ending as providing the data, the physical data only, and often somebody else takes over the physical data and fits it into the overall program. I agree that the training system should be revised so that the geophysicist is made more conscious of the fact that he should input more into the project than purely geophysical data.

S. Hancock

I find geophysical consultants the worst examples of what I am talking about - of people who provide an answer in pure physical terms, in physicists' terms, and leave it at that.

What you need, then, is one of those engineering geophysicists or a geophysicist who has been exposed to work of this nature, to look at that data and bring it to a practical answer. We have, on a number of occasions, been called in to interpret the data collected by consulting geophysicists who are really only acting as contract geophysical companies, not consultants.

E.J. Polak (BMR)

If you take all the logging that was carried out in the past and is being carried out at present, the companies don't wish to do an interpretation they want to just provide the logs. Similarly, if an engineer is doing an investigation for a cut, he requires only depths and velocities. This is not the fault of geophysicists, but the fault of the user and the usage. The geophysicist often says "pay me an extra amount of money, and I will give you an interpretation as well". Very often the engineer refuses to pay this amount.

S. Hancock

I find that very often a contract logging company is very loath to get involved in the interpretation at all. They are really a servicing contract organisation. This may be that they have been caught on this problem before. It is a serious breakdown of responsibility. I think in an organisation such as ours, which is small enough for everyone to be seeing one another regularly, and small enough to require people to do a number of different tasks, that you then generate fairly rapidly this overall understanding of where the geophysics fits into the overall picture.

J. Odins (NSW Water Conservation & Irrigation Commission)

I would just like to come to the defence of geophysics for a moment. I have a couple of extracts from editorials which have been written in the SEG bulletins, one written by Dobrin in 1971 and he is talking about this problem and how geophysicists feel about not being involved fully in a project, and he says the geophysicist must not only be knowledgeable in his particular area, but also in computer science, information theory, but also above all in geology, if he is to handle his work with proper confidence and in the proper context. A couple of years later, another editorial said "exploration geophysics is the professional activity whose sole aim is to explore the earth by physical means, and aims to find information about the earth which may be economically useful". Now on the basis of this, it gives me the impression that a lot of the geophysical people realise that there is

...s practical gap between what they can do, and what they in fact, achieved, and partly in answer to this where this rather small group in your company has found an excellent answer to this situation.

What Mr Polak was saying was that in large organisations, that gap is still there.

S. Hancock

This is so. You tend to have a geophysical department and they tend to stand off and say to the geologists, "that's our interpretation, and do what you like with it", and this is a pity. I know for example the USGS, in hydrogeology, has been plagued by this division between engineers, geologists, and geophysicists. The geologists and engineers have been fighting much longer than geophysicists and hydrogeologists and the USGS overcame the problem by putting the engineers and geologists together at the same level in the same section and said, "well, there you are. You can fight or you can work", and fairly rapidly they learned to work together. We have to achieve the same thing in hydrogeological geophysics, or geophysics and geology, and it is not helped by subdivision of departments into what are really unnatural divisions that have been created at an education stage, rather than divisions that exist in the real world of obtaining data and interpreting that data in terms of practical answers.

E.G. Wilson (BMR)

A lot does stem from the universities where you do get subdivisions of interest at a very early stage. Specialisation if anything, means isolation. What you find in fact, many universities are having courses on soil mechanics and rock mechanics as separate identities, but it is only an historical separation, or a separation in time of their development, even though the same people were associated with the development of both. With so much of the work that is coming up everywhere in our fields, we are faced with this hierarchy that separated everybody in accordance with their disciplines; now we will have to try and find a way of making them all work together on a functional basis.

Comment from the floor (Speaker from the SA Institute of Technology)

If I could speak from the professional side, I thoroughly agree with you that it goes back eventually to where people were trained and the traditional line of training they followed. In fact, we give our geologists two major courses in Applied Exploration Geophysics. One in second year and one in third year, backed up by higher mathematics in first and second year as well, and we have found from feedback that they can look at geophysical data and understand it, talk with the geophysicist in his own terms, and they can interpret geophysical data with their strong geological background; and there are more and more people being trained on this wavelength, but is is a long-term thing for the change to this type of attitude to come about.

S. Hancock

This change is not helped by the industry, either, in which the availability of work and on-the-job training for graduates varies markedly from year to year.

Mr Crawford (Darling Downs CAE)

You have talked about geology students being trained in geophysics and vice versa, but I wonder how many geophysicists in their second and third year course have had any courses on groundwater hydrology.

S. Hancock

Not many, but this seems to change with job experience because of the variety of methods and environments young geologists involved in hydrogeology seem to confront. An example of this is the A.G.U. in America, who are very active in groundwater geophysics and publish some of the best hydrological geophysics papers from that country. The hydrologists seem a little more active than the geophysicists, but, there are a vast number of hydrological papers in the transactions of that society. Such organisations are very positive in bringing disciplines together. In general, the upsurge of environmental studies is going to bring about this coalescing, this bringing together of people, even if only initially at interface committees where talk is just across the table; not only in geophysics, geology and engineering, but also in the other physical and biological sciences. This is surely a trend that is with us now, in fact, away from the high degree of specialisation, back to the people who have a broader understanding of the environmental parameters which affect or relate to their disciplines.

E.G. Wilson (BMR)

One point is that we often see engineers publish articles in engineering geological and geophysical journals. I have been trying to find where I could get an engineering geological paper published in an engineering journal. We can carry out a lot of geological and geophysical investigations, but unless we reach the engineers, we are getting nowhere. They carry the purse strings and the ultimate responsibility for a project, and they incur the ultimate responsibility for their dereliction of duty through inadequate geophysical and geological control. I think this is a problem we should think of throughout the whole of this seminar. I'm not sure how we reach the engineers.

S. Hancock

Our various professional associations of which we are members, tend to perpetuate separation of the disciplines to a degree. We tend to get along to our geological society meetings and SEG meetings etc., and we talk backwards and forwards amongst the converted. Just recently, the hydrological division of the Institute of Engineers had its conference at Armidale. There was one paper on geochemistry, one on geophysics and a couple of papers on geology. They were very well received, in fact, the editing committee went out of its way to ensure interesting, often inter-disciplinary papers, rather than people presenting another paper on building the biggest concrete mass dam in the Southern Hemisphere, for which most of the theories and practices are well established. There were separate sessions on stochastic hydrology and other theoretical aspects which tend to be produced by the universities in great profusion. Certainly this association and the Australian Water and Wastewater Association, were set up to facilitate interchange of ideas between engineers, biologists, and microbiologists. They are taking a broader look at hydrology and aspects of hydrology in general. These associations really deserve support.

E.G. Wilson (BMR)

The Australian Water and Wastewater Association in Canberra is largely composed of hydraulic engineers.

S. Hancock

I know that the A.W.W.A. is not strong in Canberra and it seems that this association is strong where the hydrology section of the Institute of Engineers is not. The hydrology section of the Institute of Engineers is very strong in Canberra; in fact, it is no longer part of the Institute of Engineers and is known as the Hydrology Society of Australia. Certainly the initial formation and aims of the A.W.W.A. arose out of dissatisfaction with the major institutions in bringing people of different disclipines together. In the past, for example, a paper on geophysics which may have been absolutely basic to a water supply project, could be rejected by many associations because it's not engineering. With the reorganisation of the Institute of Engineers, we may see a change in this policy. Even to attend the meetings of these organisations is valuable.

J. Odins (NSW Water Conservation & Irrigation Commission)

I think this problem also applies in reverse. When attending SEG meetings and geophysical meetings, I don't think I've ever heard an engineer talk. Generally they are not invited and if they come, they come only once. I think to help break this nexus, geophysicists should make an effort to invite engineers to speak.

S. Hancock

On an international level, for instance, the International Association of Scientific Hydrology performs a very useful function in this matter. Unfortunately, it does not meet very often and often very far away, generally in Europe, and it is perhaps beyond the budgets of most of our organisations to send us to the meetings of this sometimes poorly understood organisation. They are also making an attempt to break through the nexus or division of disciplines, these divisions don't really exist in practice.

D.E. Leaman (Tasmanian Department of Mines)

A lot of the problem seems to come down to what is described as geophysics. We have heard a lot about pure geophysics and applied geophysics; each of these has its narrow, or broad outlook. On the point of outlooks, the Tasmanian division of the Geomechanics Society, which is a very useful society, has a much wider outlook; in fact, they have encouraged several disciplines to join, even though it is nominally an engineers' organisation. They have organised a meeting where they invited a design engineer, construction engineer, engineering geologist, and geophysicist to speak and give an idea of the kinds of information they, in their own professional competence and discipline, can provide or require.

I have another question. You mentioned the use of I.P. Have you used it? What sort of results did you get, and was it successful?

S. Hancock

Yes, we have used I.P. It is basically a technique developed for mineral exploration and removes the effect of water on resistivity. We used it for this purpose then. We were involved in a dewatering project investigating a sequence which included steeply dipping graphitic shales and with pyrite mineralisation, so we had resistivity anomalies associated with graphite, with pyrite, with mineralisation, and with water. We had to distinguish which anomalies were due to water. By cutting out simultaneous dipole-dipole resistivity and I.P., we could eliminate the I.P. anomalies to find the anomalies in resistivity due to water alone.

In this program we also identified a major fault which was not found by drilling program or geological mapping. This is what I would call "fall-out data" - information that you are not looking for initially, but which comes out of your basic data. I might add that it took 18 months to convince the client that resistivity and I.P. were required. They were quite happy to do E.M., which proved perfectly useless for our purposes. We requested it for a fracture identification program, and the client objected because large sums had already been spent on a mineral drilling program and they claimed to know every fracture and fault. Of course, however, when a mineral geologist identifies a fault, he looks for a dislocation in a solid core, core losses are often ignored and, as a result, many of the major faults and fractures were missed because they were in areas where there was a loss of core.

We found afterwards a strong correlation between the geophysical anomalies and areas of lost core and also we found that in the six bores where they had a major water problem and drilling was abandoned, these were all on major faults, all previously unrecognised. The geophysics made them take a closer look at their core logs and forced them to decide on allocation of core losses. They are much more careful now about core loggings.

Returning again to I.P., experimentation is continuing overseas on this technique and we are keeping a close watch on the literature to keep up to date. As consultants, our own opportunities for experimentation in this, or for that matter, any field in which equipment and techniques have yet to be proven, are limited.

Unknown speaker

Could I ask you to comment on the role of the universities in all this. When discussions of this type start going, it all boils down to a communication gap which arises at the training stage. At the present stage in the Adelaide University, when one tries to talk about hydrogeology, we get the answer that by studying pure geology, we can apply it to any subject or any application. Flinders University makes an effort to get around this. It seems to me that as time goes on, in our fields more and more graduates are to be from institutes of Advanced Education, rather than from universities. Firstly, do you agree with that and secondly, do you see any problems arising from this?

S. Hancock

Yes, I would agree with the comments. I think one of the problems you have here is that universities tend to be self-generating. Most of the professors of today are the MSc's and PhD's of yesterday, and too often in fact, none of these have worked in the cold hard world outside and I would include in that cold hard world, the Government departments. Now, if this is so, then we have a recirculation of the old divisions, modified only by the fact that somebody may head off on an empire-building process and modify the division. We don't have to look only at universities to see this sort of thing happening. I think also that there is a lot of comment or criticism which could be levelled at industry for not getting back to the universities and saying "look - your course is not relevant, and does not provide that which is needed". Government departments and private practice should attempt to do this.

The Government departments, to a certain extent, have the same problem as the university in that they have these subdivisions as well, and it is terribly hard to break them down. So they are not prepared to go out to the universities and say "we want you to produce a more rounded graduate, a man who is less specialised, but has a broader aspect of learning". So I think it is going to be the new organisations that are going to produce this trend. For example, I know there is the School of Earth Resources at Armidale. Some engineers are saying "tut, tut, we'll never employ any of their people because they're not really engineers". This is infuriating because it may be that few of the graduates from this school will be employed because of this narrow approach and narrow-minded attitude.

My guess is that these graduates will be very valuable, particularly to any organisation involved in environmental studies. They are the sort of people who are needed, and it seems that the initiative to produce such graduates will fall to the new organisations to get out and break the old traditions of division of disciplines.

Unknown speaker

When you do a distance drawdown curve, do you use a minimum of three observation bores?

S. Hancock

When you use only three, you may have problems. We try to use four or more to be as realistic as possible. When you have aquifers of the type in the Townsville area, you need to be able to sort out the effects of interconnection of aquifers and therefore your pump tests have to be as long as possible, otherwise you may find that your farthest bore is drawndown more than your closest bore. All this sorts out in time of course, and it also sorts out in distance, but the original test bores were pumped for 5 to 14 days. Once we got into the actual wellfields, the tests were much shorter because we had established our broad-scale hydrogeological evaluation. The final interpretations came after the six-month pumping test; however, it is now a 7 million gallons/day wellfield and there has been a number of other bores put in as well. My guess is that when we get the data from over 2, 3, 4, and 5 years of production in the area, we may well find the capacity of that area is beyond that which we originally estimated. We have designed on a conservative basis. This is necessary for a number of reasons.

J. Odins (NSW Water Conservation & Irrigation Commission)

I have two questions. Firstly, on the interpretation of the data you mentioned the removal of the effect of bedrock depth on the resistivity traversing data. Could you explain how you did this phase? Is this a qualitative analysis, or quantitative?

S. Hancock (as advised by I. Rowan)

In the Townsville area, the granite bedrock has "infinite" resistivity with respect to the surface layers and the section of the depth probe curve corresponding to the larger electrode spacings is characterised by an ascending straight line with a 45° slope. At any point on this straight line, the half electrode spacing divided by the apparent resistivity equals the longitudinal conductance(s) of the geoelectric section.

i.e. $$\frac{\overline{AB}}{2\rho_a} = S$$

For traversing we chose a large electrode spacing such that each reading, which can be considered as a single reading of a depth probe, would have fallen on this ascending line. Thus, we could in fact calculate the horizontal variations in longitudinal conductance along the traverse line.

Now for a simple two-layer case, the longitudinal conductance

$$S = \frac{H}{\rho}$$

where: H = the thickness of the top layer

ρ = the resistivity of that layer

Therefore, if we know the values of S along a traverse line and the corresponding values of H (in this case from seismic refraction), we can calculate the values of the resistivity (ρ) along the line.

Admittedly we had more than two layers in our geoelectric section; however, the top layer, corresponding to unsaturated surface sediments, was relatively thin and uniform and contributed little to the total value of the longitudinal conductance (S). A further refinement would have been to take this layer into account.

J. Odins (NSW Water Conservation & Irrigation Commission)

My second question concerns Line TA, which I think you found to be a fairly productive line for water; you also mentioned high velocities in the saturated alluvium. Now I have been looking at the range of velocities from 4000 to 7000 ft/second, there are subtle variations in this. For instance, you show 5 to 6 and next to it 5 to 7 thousand; the upper range seems to be slightly outside what we would expect from saturated unconsolidated sediments.

S. Hancock

I think that you have to keep in mind that this thing is part of a series of coalescing alluvial fans, and over the top of that, you had alluvial material which has been carved into it and which is more or less well developed and well sorted, so you have a fairly complex random development of strata. The high values here are fairly typical of what we got on the Blue Water Basin strata, presumably of the same age and same lithology or similar lithology, and if we drill these high velocities, we get much the same results: low permeabilities. The lower velocities from 6000 down are generally the well sorted younger alluvial material.

J. Odins (NSW Water Conservation & Irrigation Commission)

Four thousand feet/second seems to be a little bit below that of saturated alluvium.

S. Hancock

Four thousand feet/second is presumably clays, very fine clays.

Mr Crawford (Darling Downs CAE)

Could you have cemented laterites, ferruginous laterites in this area?

S. Hancock

Yes. They are not uncommon in this area.

J. Odins (NSW Water Conservation & Irrigation Commission)

Did you use the lower range of velocities or higher range of velocities for selecting bore sites?

S. Hancock

We did not use seismic velocities, we used resistivity for selecting bore sites.

Unknown speaker

Have you in fact used geophysics to monitor the drainage of water from the clays in your example or case history given for the Goulburn Valley area?

S. Hancock

No, we have not. When I say the water has dropped 2 m, we only know that because the piezometers are two extensions of a hand auger deep in the area. These piezometers are now dry. We are concerned that some of the bores may be pumping more water than they need to. They don't really need to pull the water-table down 10 m or 2 m, 1 m would be sufficient. Now we have to look at the hydrological aspect of this. We've beaten the immediate problem that they had, now of course we have to look at the economics of pumping, and if they are to continue pumping 4.4 Ml/day, it is going to cost a fortune.

Mr Crawford (Darling Downs CAE)

Just wondering on the hydrological side of things, whether the salt present is part of a cyclic salt phase in the area and perhaps in time with rising and falling of the water-table and particularly with the water-table dropping, that you might expect recharge to flush out the salt; in time, you may be able to give away the pumping.

S. Hancock

We are hoping that the salt will be flushed out, but I feel that they will never be able to give up pumping for at least some of the time, so long as they keep pouring more water onto the land by irrigation than is received by the annual rainfall. I understand that in the 1890s, the original static water level was around 50 ft below the surface. With irrigation over the years, it has risen a long way.

E.J. Polak (BMR)

We have worked in a similar area. We have done 6 km of continuous dipole-dipole traversing at 10 m spacing, to N equals 12. We would do a kilometre, jump 1 km to another km, do another km, etc. In all this traversing, we have found only 6 locations where the resistivity increased so much as to indicate fresh water. My question is on how many areas or properties did you locate this fresh water?

S. Hancock

Ten properties spread over a wide area. We were surprised by this result too. We did, in fact, do 12 properties and on 2 of them we are awaiting further work. We have told the people that there is nothing in the data that is of use at the moment and the other property is, in fact, adjacent to properties where we have already established pumping stations. On the latter property, we found good-quality water O.K., but it was located in extremely fine sand which was very difficult to develop. We advised that the neighbour's pumping station would, in fact, affect his area, and that he should sit back and see what happens before incurring more expense on his property. This was the right decision, because the water-table has dropped over 1 m on his property. He is, in fact, relying on his neighbour's pump to a certain extent, but they don't mind, because this particular owner spent quite a lot of money on investigation, particularly in the preliminary stage. I don't know why our data gives better results than yours, we chose not to do dipole-dipole traversing, because it was time consuming and difficult to carry out in the confines of an orchard. We've done a lot of depth probes, but many of these depth probes gave us nothing.

E.J. Polak (BMR)

We also did a lot of depth probes in this area just west of Shepparton. Later we moved further north to north of Numurkah and on all depth probes and dipole-dipole traversing in this particular area and out to AB/2 spacing of 600 m we got a maximum resistivity of 8 ohm-m. Even in places where sand and gravel was present, there was low resistivity due to the sands being saturated with salt water.

S. Hancock

Yes, as we go north from the area, particularly towards Kerang and Pyramid Hill, the interpretation is almost reverse; we should look for the areas of lowest resistivity which contain large permeable bodies of salt water, and the problem of course is to remove this salt water, and replace it with fresh. The brines become more concentrated in the actual sands in that area, so I caution against extending a simple interpretation from one area into another. The interpretation we have here is probably O.K. for Toolamba, Mooroopna, and Shepparton areas, but moving into the more extensively salted-up areas, certainly I think our portable equipment would fail; the depth penetration would be limited, we would have to be using much more powerful equipment.

They have sodium clays in the northern parts of the plain and it is almost impossible to do anything about dewatering this area by under-drainage techniques.

E.J. Polak (BMR)

I appreciate this, but this is an important problem for much of the Murray Basin.

S. Hancock

The same situation applies on the northern side of the Murray at Wakool in New South Wales - we found exactly the same thing: good-quality waters in shallow stream sand, surrounded by aquifers containing very saline waters and overlain by clays containing saline waters.

Mr Crawford (Darling Downs CAE)

What equipment did you use there and did you have problems with penetration?

S. Hancock

The equipment used initially was an upgraded Megger and was found to be under-powered. The area was wet: in some cases, water-table was above ground level, it was winter at the time of the survey. This produced some problems. The [illegible] unit we used was a battery pack unit pushing out 540V low amperage. Later we resorted to a 440V McPhar unit, however, the battery pack and McPhar gave similar results, so we resorted mainly to the battery pack for the purposes of manouvrability within the orchards. The high voltages seemed to be required to overcome the low-resistivity surface layer; the low-resistivity surface layer affected the accuracy of depth determination to the order of 5-10 ft accuracy, but this was not critical in this case. At least 6 test holes could be put down per day and at \$3/ft, the economics of the geophysics was still viable. Our approach was to look firstly for sites, then investigate a site for depth. We could also put limitations on sites from geology. Under no circumstances would we look at an anomaly below 70 ft because from the geology of the area, we considered that this would be an aberration. Sixty feet is about the known depth of the old prior streams in the area and if you go deeper than that, you will probably get saline water in the Pliocene sands. S.R. & W.S.C. had, in fact, encountered this problem. They had a line of bores, one of which was deeper than the others and it had a salinity of 8000 ppm, the others around 2000 ppm. Initially, they thought they were dealing with just very variable salinities. Some of the sand areas were identifiable geomorphically, and in practice, the orchards tend to occupy the best areas or to have contracted to the best areas. On a number of properties, I remembered thinking that we would get nothing because there was no geomorphic evidence, but the geophysics still managed to give good results, except for the two properties mentioned earlier, one of which, in reference to Eddy Polak's question, was to the north where the salinities started to get much higher.

CURRENT PRACTICES IN GROUNDWATER GEOPHYSICS

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1. INTRODUCTION

The following notes are in no way complete but have been prepared to facilitate studies of the application of geophysics to hydrological investigations. The notes are directed principally at potential users of geophysics (geologists, planners, irrigation and local government engineers, etc.) to provide a guide to geophysical methods and a background for assembling further information if required. The potential applications and limitations of geophysics in solving groundwater problems are stressed and hopefully this will promote a greater understanding of the possibilities for using geophysics in hydrological studies.

There has been a rapid worldwide development of the application of geophysics to hydrology and it is estimated that over 300 geophysical surveys have been carried out in Australia with the purposes of finding and contributing to the development of our water resources. Appendix A gives a list of groundwater surveys conducted by the Bureau of Mineral Resources since 1947.

There are five major divisions of geophysical methods, all of which have been applied to hydrological studies. Table 1 lists these methods in descending order of importance and frequency of use in groundwater studies. These notes are concerned only with surface and airborne geophysical methods; subsurface (logging) methods are not discussed.

Several types of groundwater regimes or environments may be identified. The major types are listed in Table 2. Combinations of several of these environments are also common.

The notes that follow will first briefly describe each geophysical method and then deal with the limitations and applications of the methods in the different groundwater regimes. Geophysical methods are not always the most suitable methods of solving groundwater problems; on some locations auger drilling may provide a more complete hydrological picture of the area, at a lower cost than geophysics. The decision to use a geophysical method depends on the capabilities and limitations of the method, plus the timing and costs of the survey, and must be based on an understanding of the geologic and hydrologic problems of the area.

Table 1

Method	
1. Electrical	
Resistivity Induced polarisation Electromagnetic	Induced field from current or electromagnetic sources.
Telluric Magneto-telluric Spontaneous potential	Variations in Earth's natural electric field.
2. Seismic	Seismic wave propagation, its velocity, frequency, and attenuation.
3. Magnetic	Variations in Earth's magnetic field.
4. Gravity	Variations in Earth's gravity field.
5. Thermal	Variations in Earth's thermal field.

Table 2

Groundwater Regimes in Australia

Regimes	Comments
Alluvial (unconsolidated sediments)	Most common. Can be fresh or salt water regimes.
Consolidated sediments	Great Artesian Basin
Karst areas	
Igneous areas	Volcanics or plutonic
Metamorphic areas	

Each geophysical survey consists of three basic stages:

(1) Preliminary preparation of geological and hydrological information in which the geophysics plays a minor role. Some preliminary modelling may be necessary, however, to determine the optimum geophysical methods. The success of the survey may depend on the care with which this stage is prepared.

(2) The collection and reduction of geophysical data with a preliminary interpretation and continual assessment of results and assimilation of any new geological data provided by drilling follow-up during the survey.

(3) The final interpretation, conclusion, and verification of results involving the geophysicist, geologist, and drillers, in conjunction with the client.

2. GEOPHYSICAL METHODS

The geophysics and technology of interpretation techniques has advanced considerably to the point where many branches of applied geophysics are specialisations. The basic theoretical backgrounds of all methods are dealt with in several textbooks, although some of these are outdated in parts by recent developments. The following books are readily available and cover more than one geophysical method: Heiland, 1946; Jakosky, 1950; Eve & Keys, 1956; Dobrin, 1960; Parasnis, 1962; Griffiths & King 1965.

2.1. ELECTRICAL METHODS

The electrical methods are the most important geophysical methods in relation to groundwater studies. The details of these methods are covered in Bhattacharya & Patra, 1968; Keller & Frischknecht, 1966; Kunetz, 1966; and van Nostrand & Cook, 1966.

Electrical methods can use either the natural electric fields in the earth (the telluric current method, magneto-tellurics, and the spontaneous polarisation method) or make use of an applied electric field, as in the conventional resistivity techniques.

2.1.1. TELLURIC CURRENT METHOD

Telluric currents are natural electric currents flowing in the earth. They are generated by geomagnetism, ionospheric conditions, solar activity etc. Superimposed on these large-scale currents are localised current eddies generated by industrial activity, electrochemistry, atmospheric electricity etc. (Berdichevski, 1960; Srivastava, Douglass & Ward, 1963).

The time-dependent electric field gradients in volts/km are simultaneously measured in two directions using two lines joining a pair of electrodes 300 m (or more) apart.

The fields are measured generally in mutually perpendicular directions. In the interpretation of the method, relative intensities of the fields at the point of investig.tion with respect to the fields at a base station are used.

The method provides qualitative information on the geological structure of an area (e.g. basement relief in a sedimentary basin).

2.1.2. MAGNETO-TELLURIC METHOD

The magneto-telluric method (Berdichevski, 1960; Cagniard, 1953; Vozoff, 1972) is similar to the telluric method but it provides an estimate of the resistivity of the layers. In addition to the measurements of the variations in the telluric field, variations in the associated magnetic field in three directions, are measured. Magneto-telluric measurements at several frequencies provide information on the variation in resistivity with depth, because the depth of penetration of electromagnetic waves is a function of frequency (skin depth= $\delta = \sqrt{\rho T}/2$ where δ = depth of penetration in km)
ρ = resistivity in ohm-metres)
T = period)

Interpretation techniques usually involve comparison of observed data with theoretical curves (Srivastava, 1967) or computer-based inversion techniques.

2.1.3. SPONTANEOUS POLARISATION METHOD

The spontaneous polarisation (self-potential) method uses measurements of electric potential chat arise from local electrochemical and/or electro-filtration activity. Electro-osmosis is due to the contact of two different solutions (salt and fresh water), while electrofiltration is due to flow through a porous formation: negative charges are formed on the solid particles and positive charges are bound to the liquid and move with the liquid, indicating positive potential above the "stream". The method is used to locate the underground flow of water (Bogoslovsky & Ogilvy, 1972) and leakage from reservoirs (Ogilvy, Ayed, & Bogoslovsky, 1969).

2.1.4. RESISTIVITY METHOD

The resistivity method of prospecting relies on the resistivity contrast between different rock bodies and their response to applied electrical fields. The resistivity of a formation depends upon three factors:

1. The resistivity of the dry rock matrix.
2. The resistivity of the fluid enclosed in the rock.
3. The proportion of fluid in the rock. In rocks below the water-table the proportion of fluid is equal to the porosity of the rock.

The resistivity of dry rock

In the dry state, rocks have a very high resistivity. If they contain magnetite, pyrite, pyrrhotite, or graphite their resistivity will be low. Dry clay, loam, and marl always contain some moisture and therefore their resistivities are lower than that of dry solid rock.

The resistivity of fluids

The resistivity of a fluid depends on the amount and kind of salt dissolved in the fluid, and the temperature. An estimate of the total dissolved solids (TDS) given as its equivalent in parts per million (ppm) of NaCl can be obtained from the resistivity of the formation water using the formula of Guyod (1944):

$$Rw = 5000/C$$

where R_w is the resistivity of water in ohm-m at 25°C.
C is the salt concentration in ppm or NaCl equivalent.

Generally it is assumed that the resistivity due to a certain quantity of other salts is equivalent to half that quantity of NaCl by weight.

To reduce the resistivity of water at any temperature (t) to resistivity at a standard temperature of 25°C the following approximate formula of Dyson & Wiebenga (1957) is used:

$$\log (R_w)_{25^\circ C} = \log (R_w)_t - (50 - 2t)/3000$$

To relate the resistivity of a rock to the resistivity of its components and their relative proportions, empirical formulae have been derived. Archie's Formula (Archie, 1942) states that if the resistivity of the rock material is very much greater than that of the rock fluid then at a given temperature,

$$Rf = Rw/\emptyset^{m}.S$$

where $\emptyset$ = Porosity (fractional value)

Rf = Formation resistivity (ohm-metres)

Rw = Water resistivity (ohm-metres)

S = Water Saturation (S=1 for formation below the water-table)

m = Cementation factor

This relation allows prediction of porosity if Rf and Rw are known. If a rock shows relatively uniform grainsize, porosity can then be related to grainsize. Also if grainsize is reasonably uniform variations in Rf will indicate variation in TDS content of the water within the formation. The cementation factor is an empirically derived value varying from 1.2 for unconsolidated sediments to 2 for limestones.

Archie's Formula applies only to ideal clay-free high-resistivity matrix rocks. If the rock contains appreciable quantities of clay the conductivity behaviour does not bear a simple linear relation to the pore water resistivity. Clays are non-ohmic in their conduction properties; ions interact with the weakly charged clay particles, and the nature of this interaction depends on the ion most prevalent in solution and the type of clay (e.g. kaolin, illite, montmorillonite). The presence of clay in a porous rock generally lowers the resistivity, and estimates of porosity from the formation resistivity and water resistivity are ridiculously high. Where a clay sediment or clay-bearing rock is impervious and dry, the effective porosity of the rock, or the fractional pore spaces which are inter-connected, may be very small and the rock resistivity very high. If clay is present, hydrological parameters such as porosity cannot always be easily predicted.

The above mentioned considerations indicate that the resistivity of a rock can vary considerably from about 1 ohm-metre for unconsolidated sediments saturated with saline water to several thousand ohm-metres for dry non porous rock and even dry sand and gravel. The resistivity of sands and gravels saturated with fresh water ranges from about 15 to 600 ohm-metres.

Clays vary in resistivity from less than 10 ohm-metres to several hundreds of ohm-metres when saturated with fresh water. Resistivity data from BMR geophysical surveys prior to 1968 are given by Hart (1970).

In resistivity field work average values of resistivity over large volumes of rock strata are measured. The volume is increased with deeper investigation. The resistivity of a rock may depend on the direction of current flow through the rock due to anisotropy. This anisotropy may be due to the micro-structure of the rock, the bedding, the direction of deposition, or lava flow etc.

Four main types of resistivity are referred to in resistivity investigations.

The true resistivity is either measured in the laboratory or interpreted from resistivity field data.

The apparent resistivity is the resistivity measured in the field assuming the earth to be a medium of uniform resistivity. The apparent resistivity for a non-uniform earth depends on the electrode configuration (or measuring geometry) and electrode separation. The variation of apparent resistivity with electrode separation is diagnostic of true resistivity variations with depth in the earth.

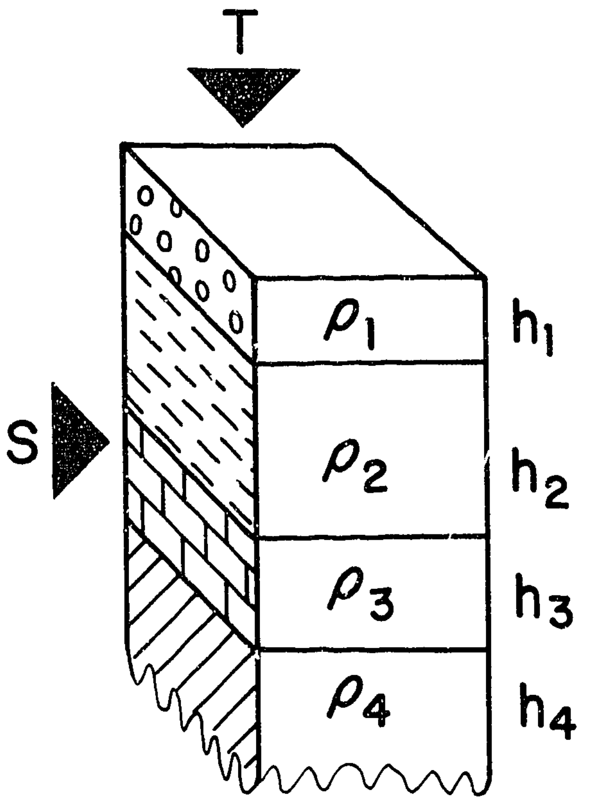
The transverse resistivity is the resistance per unit length across a series of beds and is applicable in the case of current flow across the resistivity layering. This will be the case when a series of resistive beds are bounded by conductive layers. The transverse resistivity is the sum of the product of resistivity and thickness of all the layers, divided by the total thickness (Fig. 1).

The longitudinal resistivity or the longitudinal conductivity is applicable for current flow along the (resistivity) layering as in the case of conductive beds bounded by resistive layers. The longitudinal conductivity is the inverse of the longitudinal resistivity and is defined as the sum of all the ratios of thickness to resistivity divided by the total thickness.

Field methods and equipment

In resistivity prospecting a current I is introduced into the ground through at least two current electrodes A and B, and the potential difference is measured between two potential electrodes M and N. The principles of superposition and reciprocity apply so that when current electrodes are interchanged with potential electrodes, the measured potential difference will not change.

The current introduced into the ground may be either a direct current (d.c.) or alternating current (a.c.). The use of d.c. requires



FOR VERTICAL CURRENT FLOW
TRANSVERSE RESISTANCE

$$T = \sum_i \rho_i h_i$$

FOR HORIZONTAL CURRENT FLOW
LONGITUDINAL CONDUCTANCE

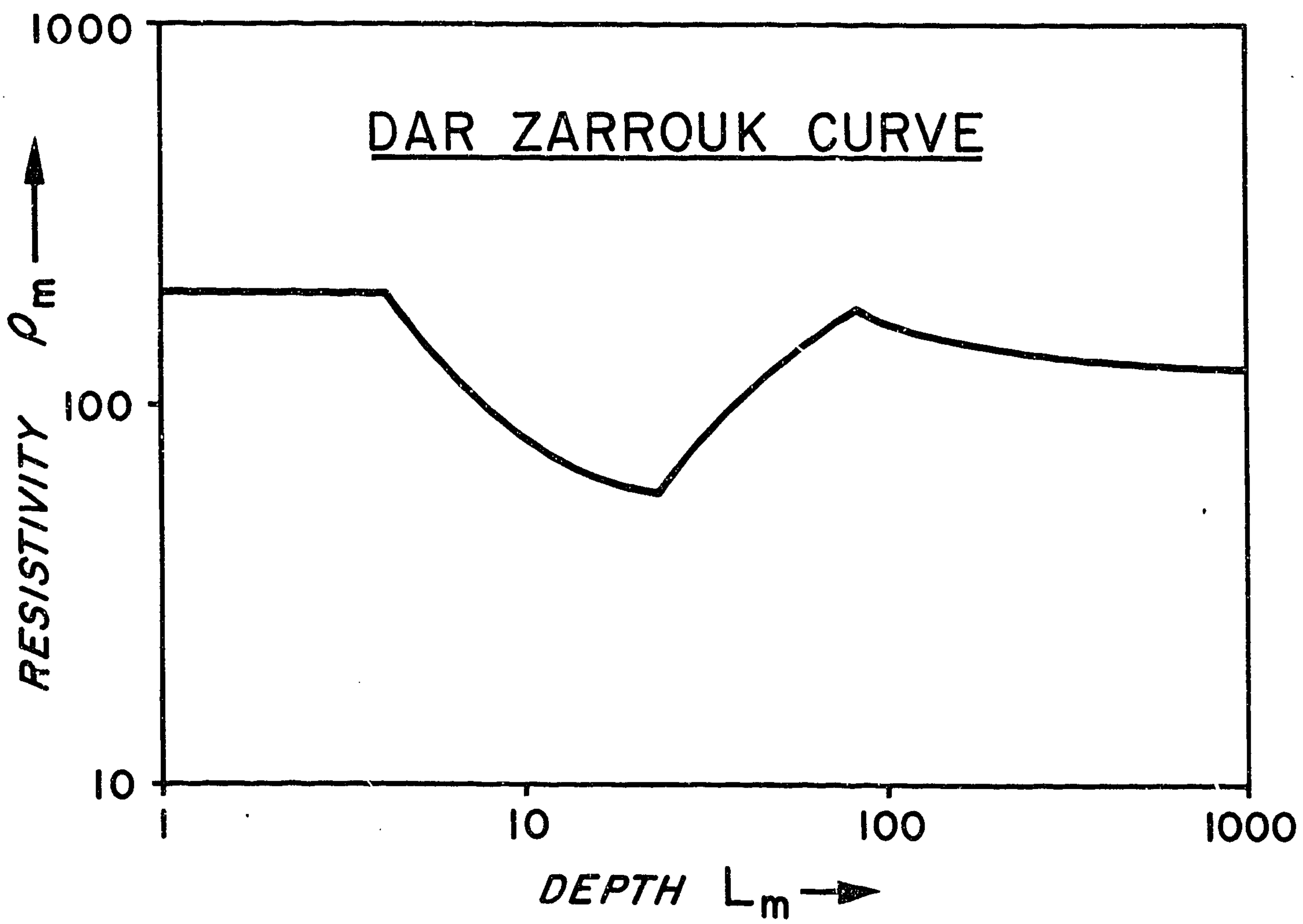
$$S = \sum_i \frac{h_i}{\rho_i}$$

DAR ZARROUK PARAMETERS

$$\rho_m = \sqrt{\frac{T}{S}}$$

$$L_m = (\lambda z)_m = \sqrt{TS}$$

λ = Coefficent of anisotropy
z = Total thickness = $\sum_i h_i$



a special measuring electrode to avoid polarisation voltages. The use of a.c. has several advantages such as smaller generating equipment, easier amplification, and filtering. The major disadvantage is the skin effect, especially where the near-surface strata are highly conductive, resulting in a decrease in current density with depth (Kunetz, 1966).

Two types of resistivity work may be done: resistivity depth probing and resistivity traversing. The purpose of depth probing is to determine vertical variations in electrical resistivity, while resistivity traversing locates lateral variations in resistivity.

The method of positioning the electrodes is the main part of the field procedure. At least 20 different electrode arrangements have been used in hydrology. Each of the major textbooks gives several electrode arrays. Unfortunately some arrangements are known by several, often confusing names. We will concern ourselves with the few generally used. (Figs. 2 & 3).

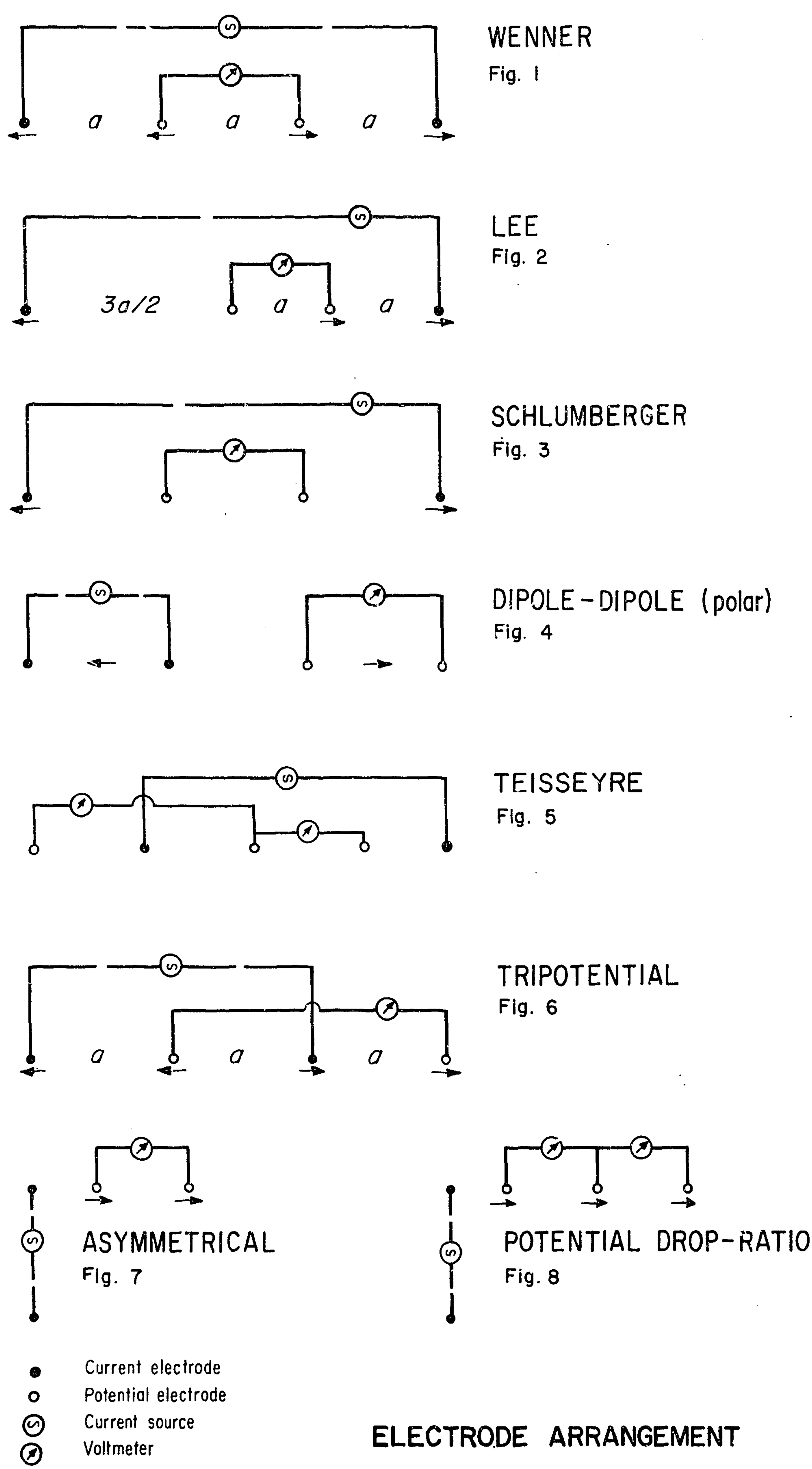
The Wenner electrode configuration was introduced in 1915 (Wenner, 1915) and from the beginning was generally accepted, especially in the English speaking countries. Slight modifications were introduced to detect near-surface inhomogeneities (Lee arrangement). In the Wenner system, four electrodes spaced "a" are moved simultaneously, and therefore it requires four field assistants. The method is highly susceptible to lateral changes in surface resistivity.

The development of the Schlumberger method (Schlumberger, 1932) led to a great increase in the use of the resistivity depth probing method, especially for deeper probing. It requires shifting only two electrodes at a time. This is the most common configuration used in depth probing and is less susceptible to lateral changes.

In the dipole-dipole arrangement (Alpin et al., 1966; Keller, 1966) there are several geometries of electrode arrangement, and some of them have smaller equivalent depth penetration than others; the method requires a much more powerful current source.

The Wenner arrangement has a greater depth of investigation where a thick upper layer is of high resistivity. The Schlumberger arrangement has higher resolving power for a thin low-resistivity bed interbedded with

Fig. 2



ELECTRODE ARRANGEMENT

Record No. 1975/133 and 1976/108

G 16-105A

BILATERAL BIPOLE DIPOLE EQUATORIAL

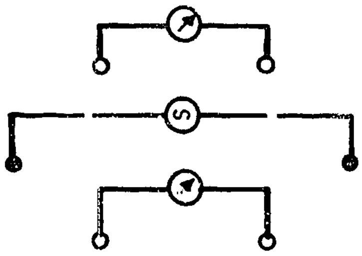


Fig. 9

LATEROLOG

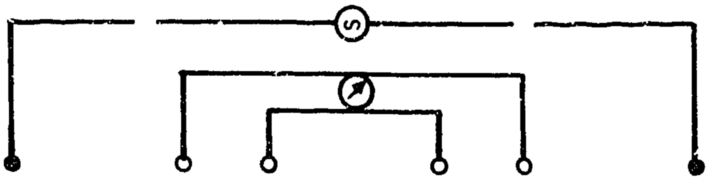


Fig. 10

COMBINATION

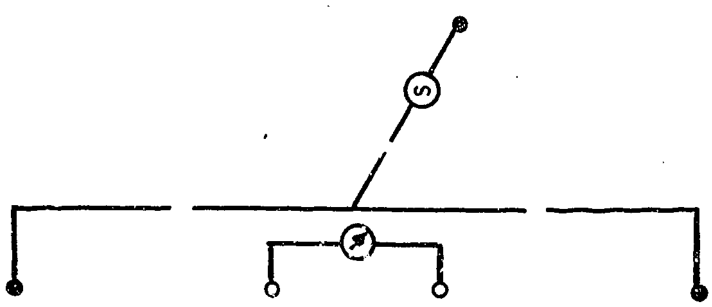


Fig. 11

SUBTRACTION OF FIELDS

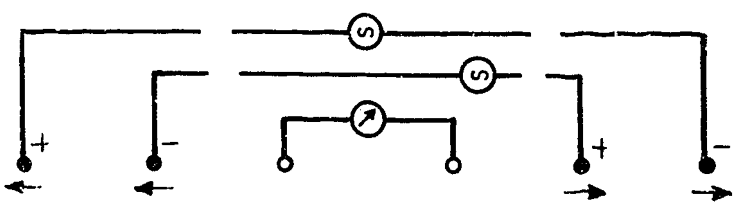


Fig. 12

CROSSED FIELDS

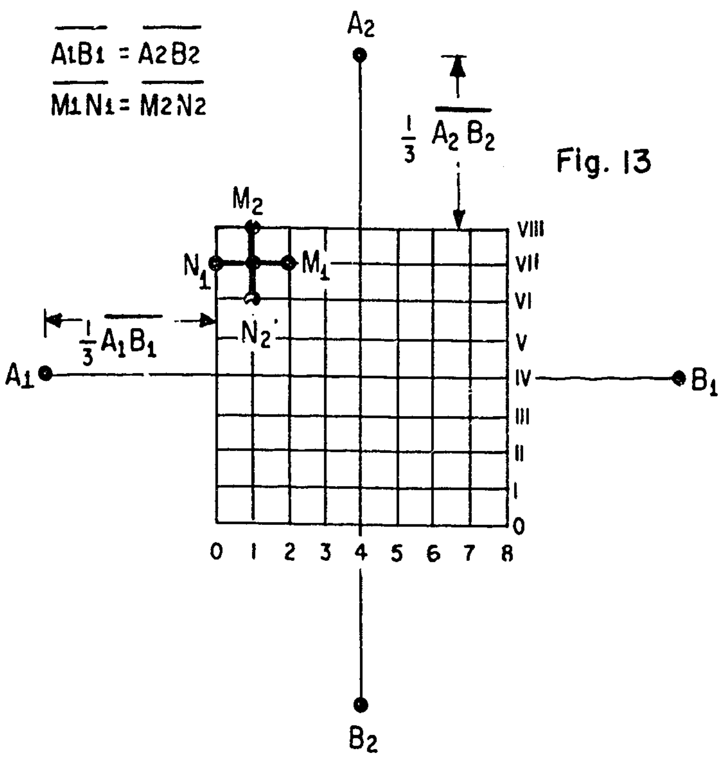


Fig. 13

SECOND DERIVATIVE

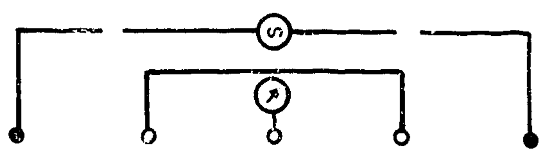


Fig. 14a

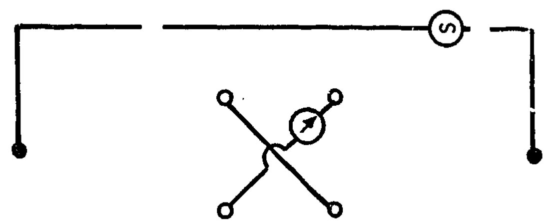


Fig. 14 b

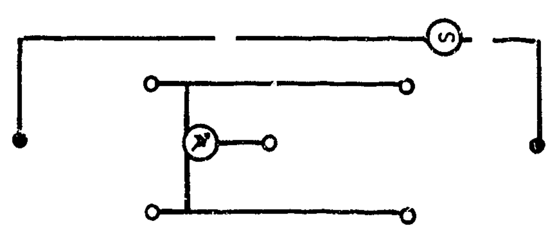


Fig. 14 c

ELECTRODE ARRANGEMENT

Record No. 1975/133 and 1976/108

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high resistivity beds. The depth of investigation for different electrode arrangements is discussed by Apparao & Roy (1971). The results obtained with Schlumberger and dipole-dipole (equatorial) arrangements are given by Zohdy (1969a).

These three electrode arrangements are used in the majority of surveys and they are often combined. The Schlumberger or Wenner is used for small electrode spacings followed by dipole-dipole for larger spacings in deep electrical probing. From these arrangements several modifications have been evolved to provide the following advantages:

1. Distinguishing near-surface irregularities
2. Obtaining better resolution
3. Increasing the depth of investigation
4. Simplification of field procedure

As the Wenner arrangement measures larger voltages than the Schlumberger it is more accurate when used in low-resistivity areas. In Canada there is evidence of a return to the Wenner arrangement, especially in areas of sea water intrusions into aquifers (Lazreg, 1972).

The Wenner arrangement has been modified to provide information on lateral inhomogeneities. Jakosky (1950) introduced a fifth electrode in an equidistant arrangement to obtain indications of sloping interfaces, and later Carpenter & Habberjam (1956) interchanged one inside potential electrode with the adjacent current electrode, introducing the so-called tri-potential electrode arrangement. In a further development of the tripotential method (Habberjam, 1967; Habberjam & Watkins, 1967) a method of smoothing the field curves was devised. From our experience the method may introduce, in interpretation, an additional layer of medium resistivity between two layers with a high resistivity contrast.

The asymmetrical method (Heiland, 1946) gives results equivalent to the Wenner arrangement, but limits the number of electrodes advancing during field work to two or even one electrode.

Using non-uniform spacing the above method was modified to give the so-called Schlumberger "L" curves (Zhody, 1970) and also the pole-multidipole method (Merrick, 1974). In the potential-drop-ratio method at least three potential electrodes are used and the ratio of the potential between the centre and each outer electrode is measured.

To measure lateral changes in the electrical field, the potential-drop method as shown by Kunetz (1966, page 32) has been changed by superposition of an identical arrangement rotated by 90 degrees. The method gives not only the anisotropy of the near-surface rock, but also a change in the depth to the lower layer.

Several special arrangements were introduced to increase the depth of investigation: the laterolog arrangement (Apparao & Roy, 1973), the combination arrangement (Dutta, Base & Saikia, 1970), and differential resistivity sounding (Zohdy, 1969). Although these methods make resolution of beds at greater depths possible, they are very susceptible to lateral resistivity changes.

Some suggested specifications for resistivity prospecting equipment are given below; however, it is impossible to list all the requirements.

The current source must be capable of delivering a constant current over the time of the potential difference measurement. The required current depends on the depth (electrode spacing) from which we require information, and varies from 0.1 amp for work up to AB=100 m, to 8 amps for spacing AB of 15 km. The output voltages of the transmitter should vary from about 12 volts to at least 800 volts. The current source should preferably be provided with facilities for reversing the current periodically, either manually or by electrical reversing circuitry. The current is introduced into the ground through steel electrodes. A normal electrode is capable of carrying approx. 1.5 A currents, and if necessary more electrodes can be used in parallel.

The potential measuring equipment is generally a multimeter of high input impedance (at least 10 K ohm) with a capacity to read down to 10 microvolts for deeper investigations. Ancillary equipment should include a spontaneous potential backing-off device and chart recorder for recording the signal in high drift.

Resistivity Depth Sounding Interpretation

The most common assumption in the interpretation of depth sounding data is a uniform layered earth. This is a simplistic assumption in most cases but is necessary because of the complexities of the mathematics of even the simplest geometries. Several authors have dealt with resistivity variations other than a simple layered earth. Geometries considered in the literature include a fault (Zohdy, 1970), an outcropping dyke (Naidu, 1966), a hemispherical sink (Cook & van Nostrand, 1954), an outcropping elliptical cylinder (Mundry & Homilius, 1972), and a buried sphere (van Nostrand & Cook, 1955). Kunetz (1966) considers the effect of two-dimensional horst and graben features. More recently Lee (1972 and 1971) has developed a method for direct interpretation of resistivity data over a generalised two-dimensional structure, though the method has not been regularly applied. All these geometries are simplified and of limited application. These notes will consider only layered earth interpretation methods. Deviations from a layered earth are considered to be lateral inhomogeneities.

The interpretation methods in predominant use have been largely so-called indirect methods. In these methods the field data have been matched either exactly to theoretical sounding curves calculated by computer or available in albums of theoretical curves, or matched approximately to simple two- and three-layer curves used in conjunction with empirical auxiliary graphs. In the earlier days, approximate graphical methods of interpretation were used.

The earlier graphical methods (Tagg, 1934; Rosenzweig, 1940; Longacre, 1945) suffer from rapidly deteriorating accuracy of interpretation for more than two layers; however, they enjoyed a brief revival in the early sixties in the interpretation of magneto-telluric sounding curves. The advantage of these methods is that it is possible to apply them to incomplete or distorted sounding curves. Moore (1945) proposed a method of graphical interpretation and reported greater accuracy in delineating channels buried beneath alluvial cover. Sanker Narayan et al. (1967) proposed a similar method.

The auxiliary curve matching techniques (Hummel, 1932; Ebert, 1943; Cagniard, 1952; Koefoed, 1960) use empirically derived auxiliary graphs to successively combine upper layers into one layer to obtain an approximate value of resistivity and thickness of succeedingly deeper layers. Pascal (1970) gives an excellent review of the philosophy and comparative merits of these methods. Zohdy (1968) and Orellana & Mooney (1966) also describe these methods of interpretation. These auxiliary curve methods deteriorate in accuracy for four or more layers, though five-layer interpretations are possible in favourable circumstances (Homilius, 1961). Until recently the auxiliary curve techniques were the best available interpretation method in the field and the preliminary interpretation in the second stage of the geophysical survey (Section 1) was thus only an approximate interpretation. Numerous albums of standard 3- and 4-layer curves are available to assist in the auxiliary graph interpretation method: for the Schlumberger configuration (Compagnie Generale de Geophysique, 1963; Flathe, 1963; Orellana & Mooney, 1966; Rijwaterstaat, 1969), and for the Wenner configuration (McMurray & Wetzel, 1937; Mooney & Wetzel, 1956; tables published in Orellana & Mooney, 1966 are plotted in Lazreg, 1972). Transformation of the dipole-dipole curves to Schlumberger curves is possible (Patella, 1974). The auxiliary curve-matching techniques suffer from the problem that the experience of the interpreter influences the interpretation, and this is a serious limitation.

The increased use of computers since the late sixties has meant that the final interpretation of resistivity data can now be carried out at office headquarters using a theoretical resistivity curve program to obtain a more or less exact match of a theoretical curve to the field data. More recently, particularly since 1971 with the publication of Ghosh's paper on the convolution method for calculation of resistivity sounding curves (Ghosh, 1971b) and with the advent of portable programmable desk-top and pocket calculators (such as the HP65), it is now possible for field parties to calculate theoretical resistivity sounding curves in the field. For example a six-layered curve can now be calculated on the HP65 in less than three minutes. This will greatly improve the second stage of the geophysical survey and should contribute greatly to the success of resistivity surveys in the future.

Several algorithms for the calculation of theoretical sounding curves are given in the literature (Vozoff, 1958; Mooney et al., 1966; Nabighian, 1966; van Dam, 1965; Kunetz & Rocroi, 1970). Vozoff (1958), Zohdy (1975), and Marsden (1973) use iterative methods to derive a layered solution which matches the input field data. The method of Zohdy (1974, 1975) provides a scientifically based method of adjusting an approximate auxiliary curve interpretation to a final solution which matches the field data and also allows an estimate of the range of possible solutions that satisfy the field data. This method is needed to replace the often ad hoc adjustment procedures which are (often) prone to individual interpretations. The method is at present cumbersome for field use but may become more feasible as the computing facilities of field parties are upgraded with inevitable improvements in technology of portable computers.

Recent developments by European researchers have been towards office-based interactive interpretation in which ranges of equivalence of solutions can be obtained from field data (Griveau, 1974, 1975; Johansen, 1974).

The major problem confronting the resistivity method is the problem of "equivalence". Several different layer configurations may produce the same resistivity sounding curve, and thus incorrect interpretations are possible if the full significance of the range of equivalence of solutions is not appreciated. Several authors discuss the law of equivalence (Keller & Frischknecht, 1966; Kunetz, 1966; Koefoed, 1969; Griveau, 1974; Henderson & Emerson, 1969). Two main types of equivalence may be identified for a series of layers. Series of layers with the same transverse resistance overlying conductive layers may produce the same sounding curves. This is denoted as T equivalence. Similarly, series of layers which have the same longitudinal conductance may produce similar sounding curves if they overlie resistive layers. This is denoted as S equivalence. In the absen of borehole control or reasonable estimates of either resistivity or thickness of the layers in the earth, considerable ranges of resistivity or thickness can be interpreted from the field data. This limitation of the resistivity method must be kept in mind when applying the technique.

Koefoed (1968) and Ghosh (1971a) give methods of direct interpretation of resistivity data to yield a solution of the resistivity layering. The methods involve evaluation of intermediate functions related to the resistivity layering, the so-called kernel function, raised kernel function, or resistivity transform function. The resistivity layering can then be calculated from the intermediate functions by graphical procedures. The methods are still restricted by the law of equivalence (Koefoed, 1969) and by the fact that any errors in the field data are compounded in the evaluation of the intermediate functions. The Ghosh convolution method (1971a) has speeded considerably the direct interpretation method. Marsden (1973) uses a direct interpretation technique to derive a starting model for his iterative curve-matching computer program.

The interpretation method of Zohdy (1974 & 1975), with the more recent research of Griveau (1974 & 1975) and Johansen (1974), in utilising generalised solutions to the resistivity layering and then combining the layers to produce particular solutions, represents the state of the art in resistivity sounding interpretation at the present time. Future research appears to be towards extending these methods and aiming for flexibility of interpretation and full utilisation of the equivalence law in the interpretation process. Computer technology improvements will, in time, enable these methods to be regularly used in the field office.

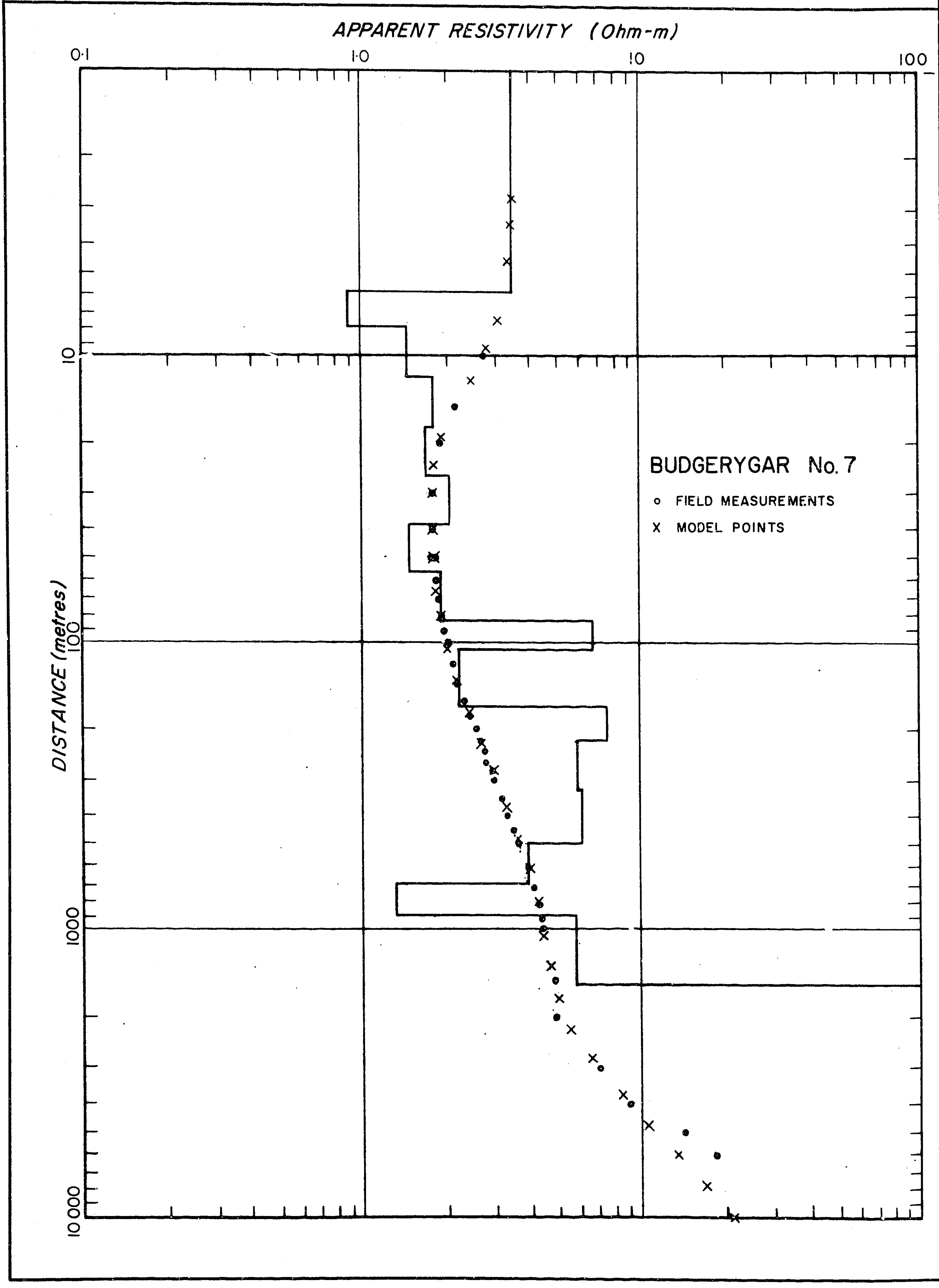
Figure 4 shows an example of a depth probe interpretation. The Budgerygar No. 7 depth probe was taken during a groundwater survey in the Yaraka area of western Queensland. In this area in the Winton Formation (Cretaceous) limited supplies of fresh water are available at shallow depths (200-300 m). The overlying beds generally contain saline water. On this survey depth probing was carried out using the Schlumberger arrangement to AB = 4 km except for one depth probe, Budgerygar No. 7, where AB = 12 km was reached. The Zohdy computer program has been used, and the ~~right~~ left part of Figure ~~5~~ 4 shows a comparison of field measurement points with the computer-calculated points and the model. The correlation between field and model points is very good except for the deepest section, where the steep slope of the field curve may indicate either an inclined interface or errors in measurement.

The interpretation of the depth probe on a linear scale is compared with the electrical, seismic, and geological log in the ~~left~~ right side of Figure 4. The correlation between the resistivity interpretation and the log of the bore is very good except for a low-resistivity zone in the Wallumbilla Formation. It is possible that the depth probe, which is 30 km distant from the bore, is cut by a fault, which was noted on the seismic traverse at the depth probe. Comparison with the seismic reflection data shows that some of the resistivity boundaries were also located by the seismic reflection method.

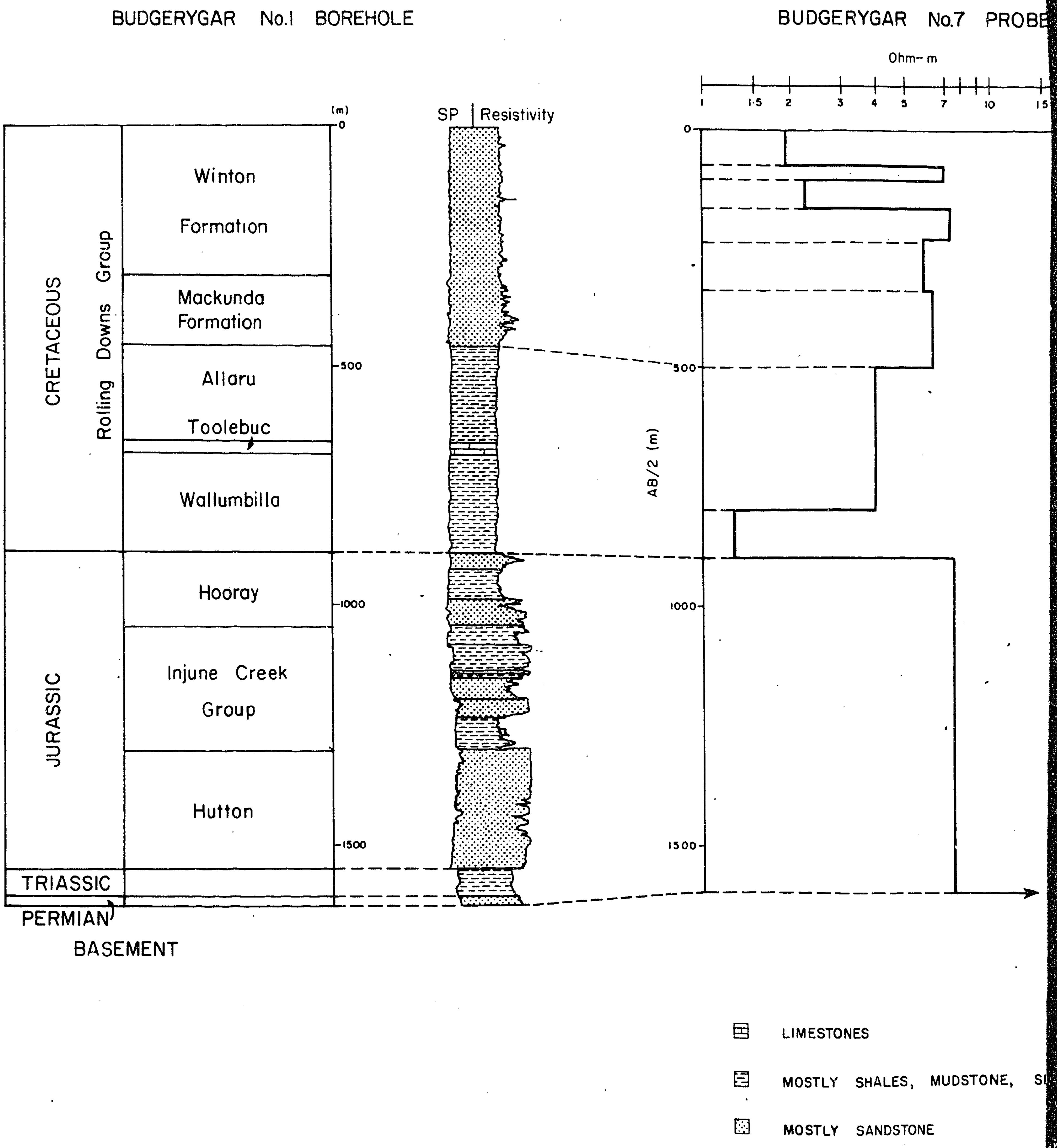
Resistivity traversing methods

The resistivity sounding method, like drilling, gives depth information at only one point. Often a reconnaissance technique is needed to investigate large areas and provide data on lateral changes in resistivity and so delineate areas of interest for further detailed investigation. Resistivity traversing provides such a technique.

In the simplest application of the technique the electrode array spacing is kept constant and the array is moved at fixed intervals recording resistivity values. The effective depth of investigation is related to the electrode spacing and can be "focused" to a particular range of depths of interest by a suitable choice of electrode spacing. Initially several resistivity soundings in the area will provide data for choice of a suitable electrode spacing for traversing.

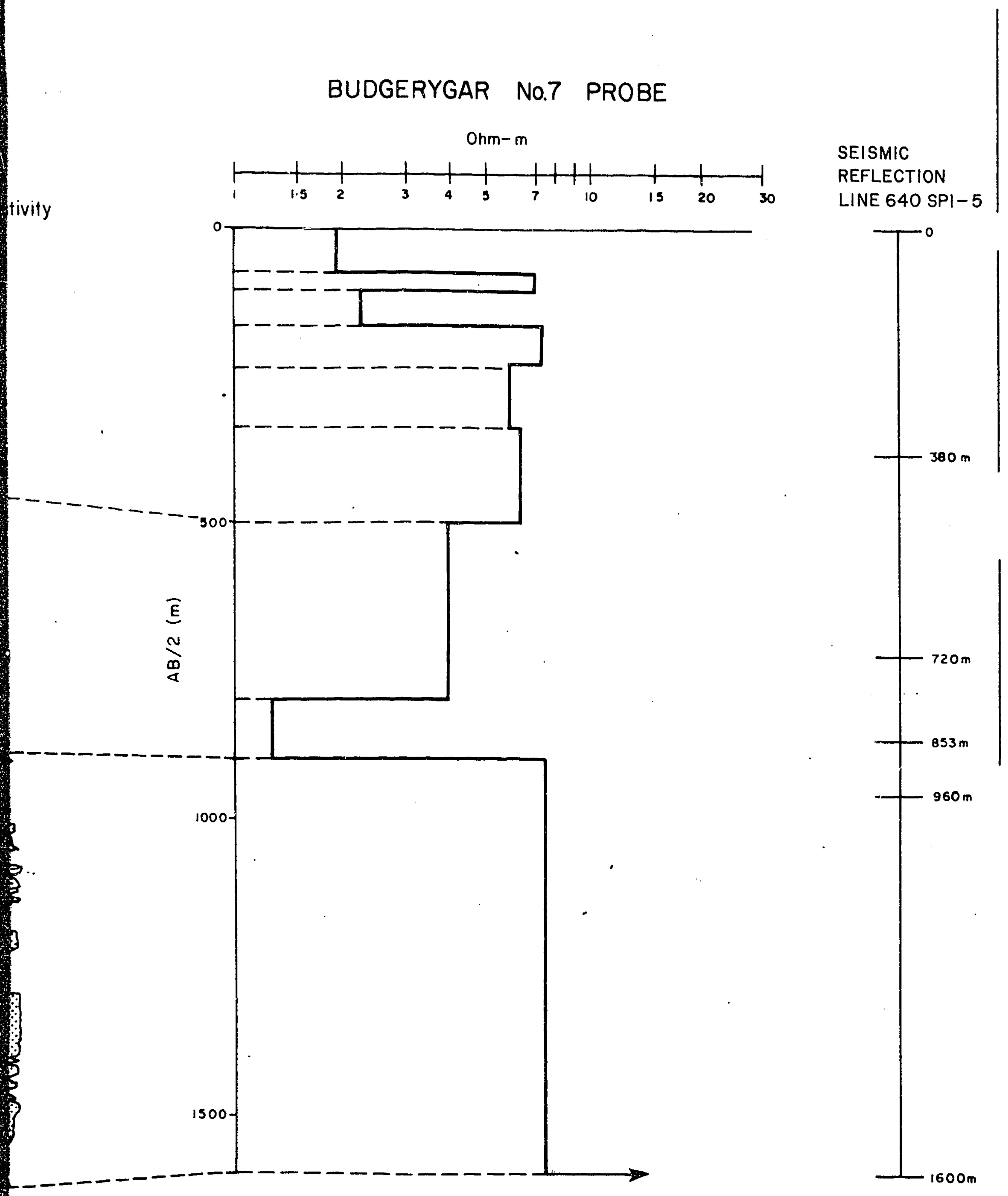


APPARENT RESISTIVITY (Ohm-m)
0·1
1·0
10
100
DISTANCE (metres)
10
100
1000
10 000
BUDGERYGAR No. 7
o FIELD MEASUREMENTS
X MODEL POINTS



CORRELATION RESISTIVITY AND DIST

FIG. 4.



LIMESTONES

MOSTLY SHALES, MUDSTONE, SILTSTONE

MOSTLY SANDSTONE

CORRELATION RESISTIVITY AND DISTANCE FOR BUDGERYGAR No. 7

In the case of resistive basement, traversing with the electrode spacing at a value sufficiently large to be sampling the apparent resistivity on the steep ascending bottom asymptote of the sounding curve will enable variations in the S value (Fig. 1) of layers overlying basement to be measured. This will delineate areas of generally high or low resistivity above basement.

Similarly with conductive basement at large electrode spacings, the variations in the T value (Fig. 1) of the layers overlying basement can be detected. Figure 5 shows an example taken from a survey in Cape York Peninsula to locate narrow, buried stream channels in laterite-covered areas. The basement in the area is conductive shales. The half Schlumberger traversing technique responds to the decrease in transverse resistance T over the permeable sand channel (Pettifer et al., 1976).

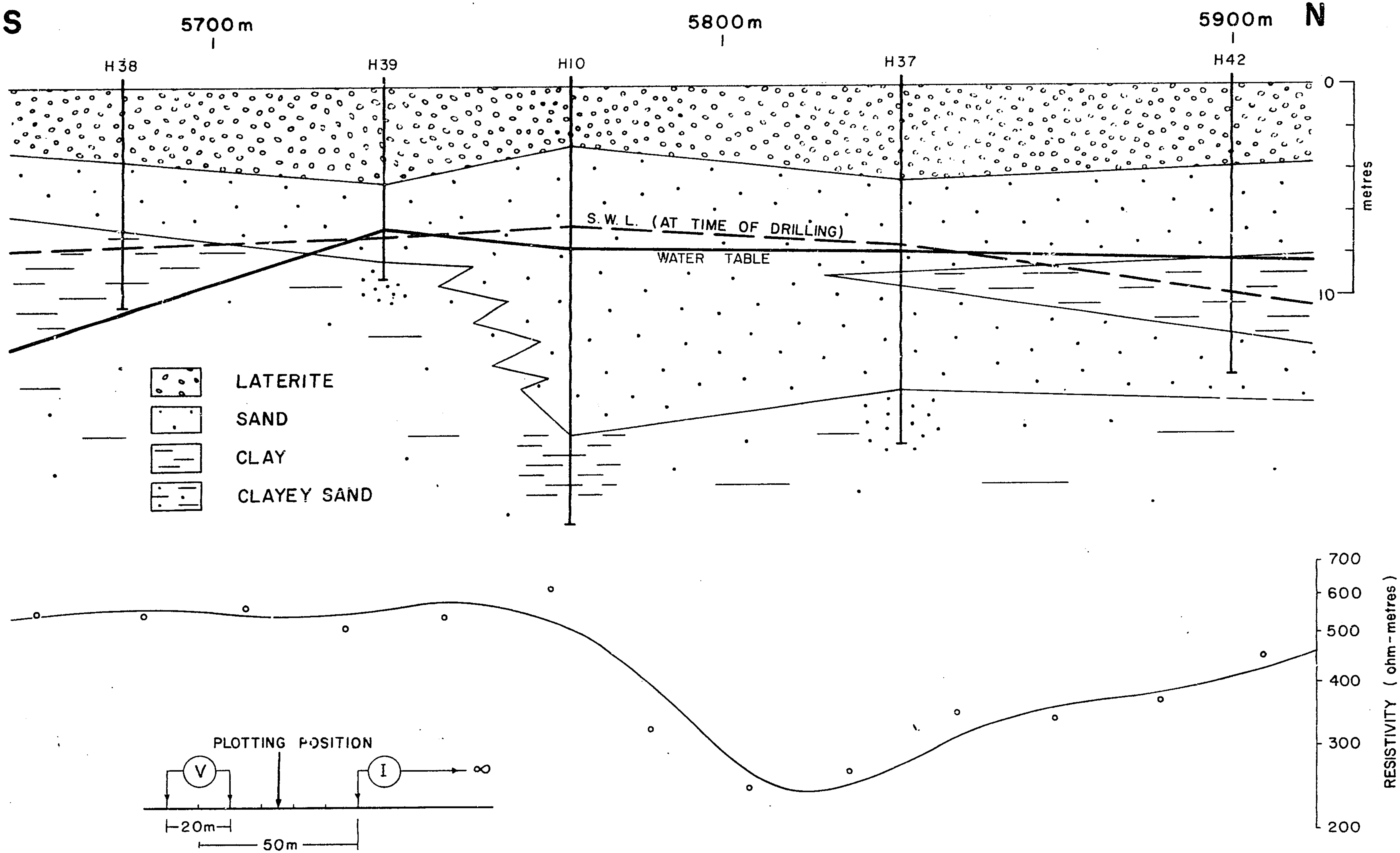
The gradient array method described previously is a technique for detecting resistivity variations over an area, and is a variant of the traversing method.

Traversing at various electrode spacings is often useful in defining resistivity variations both with depth and laterally. The dipole-dipole technique employed in I.P. work (Section 2.1.5) is a combined traversing-sounding method.

Interpretation of the traversing methods is generally qualitative although in some circumstances quantitative techniques can be applied (Cook & van Nostrand, 1966).

2.1.5. INDUCED POLARISATION METHOD

Conduction in rocks is either electrolytic (i.e. by ions in solution in the pore water) or electronic (as in metallic-type conductors, e.g. oxides, sulphides, graphite). Clays conduct electricity by electronic mechanisms, and ions in solution are absorbed into the clay structure. The conductivity of the clay depends on the concentration of the ions in solution. When an electric current is applied suddenly the concentration of the absorbed ions in the clay changes. This change is not instantaneous and is manifested as a quick build-up of charge on the surface of the clay particles. When the current is removed the concentration of absorbed ions returns to equilibrium. This process is manifested as a decay of the built-up charge on



D54/A/14

Fig. 5

Detailed section, with pole-dipole traversing data the clay particle, or "overvoltage response" (Bhattacharya & Morrison, 1963). This effect is more commonly known as induced polarisation or I.P. Montmorillonite clays show the highest I.P. effects, illite clays have medium I.P., and kaolin clays the lowest I.P. (Vacquier et al., 1957).

Metallic conductors disseminated in porous rocks have a build-up of charge on the mineral particle surface, which also produces I.P. effects, and these are generally much larger than clay I.P. effects.

In field measurements the I.P. effect is noticed when a direct current is switched on or off. Two methods of measuring I.P. effects are used: time domain and frequency domain. In the time domain method the decay of voltage is measured when the applied current is removed. The so called "chargeability" (Seigel, 1959) which is the ratio of the area under the voltage decay curve to the steady state voltage measured with the current applied, gives a measure of the I.P. effect. In the frequency domain method two square-wave currents of different frequencies (e.g. 1 and 10 hertz) are applied, and the percentage decrease in measured resistivity from the low to high frequency (the so-called "frequency effect") gives a measure of the I.P. effect (Bodmer et al., 1968). The apparent resistivity can also be calculated from the received voltage with the applied current. The theory of the method is covered in Vacquier et al. (1957) and Seigel (1959).

Rocks of the same resistivity may have different I.P. effects (e.g. clean sands with brackish water, and clay sands). Attempts at quantitative interpretation of aquifer characteristics from I.P. effects have been made (Sumi, 1970). Vacquier et al. (1957), Lazreg (1972), Barker (1974) and Bodmer et al. (1968) give field examples on the application of I.P. methods to groundwater studies.

The field methods use either depth probing or profiling (Coggon, 1973) often supplementary to resistivity measurements. The interpretation of I.P. soundings is by curve-matching procedures (Seigel, 1959; Frische & Butler, 1957; Barker, 1974; Patella & Schiavone, 1975; Patella, 1973). Continuous profiling by the dipole-dipole arrangement is common, and standard models have been published (Hallof, 1967; Hohmann, 1975).

Measurements of magnetic fields on or over the ground due to currents in the ground can also give information as to the I.P. characteristics. This is the basis of the magnetic induced polarization (M.I.P.) method.

2.1.6. ELECTROMAGNETIC METHODS

The electromagnetic (EM) methods measure the magnetic field resulting from electric current in the ground. The current may be applied either by two electrodes or by electromagnetic induction from alternating current in a coil on the surface. The subsurface current distribution is influenced by the resistivity of the rock, and in low-resistivity zones there will be a concentration of current lines. This produces a higher secondary magnetic field on the surface, and vice versa. The secondary magnetic field has the same frequency as the primary field but not the same phase or orientation. The secondary magnetic field induces current in a receiving coil located on the surface. The EM method can also be used as an airborne method (Culley, 1973).

The depth of investigation for conductive bodies in the electromagnetic methods depends on the applied frequency and the spacing between the transmitter and receiver loops, so the methods can be used for depth probing and horizontal profiling. The methods lack the resolution and penetration of the resistivity methods, but they are more rapid and less expensive.

The electromagnetic methods may be grouped according to the frequency of the transmitter source. The lower-frequency methods are most commonly used and can be used with either vertical or horizontal loops, e.g. Slingram and Turam; these methods deal with frequencies from about 240 Hz up to 5000 Hz (Bosschart, 1968).

The VLF-EM (Very Low Frequency Electromagnetic Method) uses the electromagnetic field produced by VLF communication stations located in several countries. In Australia three stations can be received: Tokyo (15.2 kHz), Honolulu (17.7 kHz), and North West Cape (22.8 kHz). The "depth of penetration" is very low. The skin depth is small, only 10 m for the low-resistivity alluvium of the Murray Valley flood plains (3 ohm-m). The method is fast and simple to use (Paterson & Ronka, 1971).

Electromagnetic sounding methods are becoming increasingly popular for groundwater studies in India (Patra, 1970) and areas of the USA (Ryu et al., 1972). There the method is ideally suited because of high surface resistivity environments, and because there are difficulties in injecting current into the ground in conventional resistivity soundings. Such an area is the laterites and heavily leached soils that are subject to monsoonal rainfall in the far north of Australia.

The method has not been widely used in Australia, possibly because of low surface resistivities which are commonly found, particularly in the arid areas of most of Australia. The EM methods have found their main application in mapping of low-resistivity zones (faults, shear zones, orebodies, etc) and would be most suited to groundwater studies in hard-rock areas.

2.2. SEISMIC METHOD

The seismic method, after electrical methods, is the one most used in hydrological work. A description of the method can be found in any geophysical textbook; the following references deal only with the seismic method: Dix (1952), Galperin (1974), Musgrave (1967), Slotnick (1959), Tucker & Howard (1973), and White (1965).

A mechanical disturbance is produced on the surface or in a borehole by the detonation of a charge or by a mechanical impact, the disturbance being propagated in all directions. A receiving unit some distance away records the earth's vibrations either photographically or on a magnetic tape with the time of the impact and timing marks every 10 milliseconds. On these records the interpretation of the geological and hydrological conditions is based.

From the disturbance three different types of waves are propagated in all directions: longitudinal or "P" wave, transverse or "S" wave, and Rayleigh waves. The longitudinal and transverse waves can be refracted, diffracted, and reflected at any velocity discontinuity.

The speed of propagation (the word velocity is used in seismic work for the speed of propagation), of longitudinal waves is a characteristic rock property. Table 3 gives the velocities of propagation of seismic waves in several different rock types.

Table 3

Rock Type	Seismic velocity in m/s
Soil	200-600
Water	1450-1500
Alluvium (dry)	600-1200
Alluvium (wet)	1400-1800
Bedrock weathered	900-2400
Bedrock jointed	2000-3500
Bedrock unweathered	3000-6000

Variation in seismic velocity depends on many factors. In alluvium the seismic velocity depends on:

Composition - The velocity in dry sand is between 400 and 1200 m/s. The higher velocity is for sand containing more boulders. The presence of fine particles decreases the seismic velocity, and in loose, uncompacted sand a velocity as low as 300 m/s may be recorded.

Moisture content - The velocity in fully water-saturated sand is higher than the velocity in water (about 1500 m/s). The presence of boulders and gravels may increase it to 1800 m/s. The highest seismic velocity ever recorded in river deposits was 2500 m/s, where floaters up to 2 m diameter were bedded in sand and gravel. The presence of clay and silt lowers the seismic velocity, and in fully saturated clay the velocity drops below that of the water.

Generally, however, the small differences in velocity between different kinds of fully saturated alluvium (Paterson, 1956; Shumway, 1960) are below the accuracy of ordinary seismic surveys.

Density and porosity - These two characteristics are very dependent on each other. The less porous material shows higher density. Therefore the coarser gravel shows higher velocity as it is less porous and denser than fine sand. (Wyllie, Gregory & Gardner, 1956).

In bedrock the seismic velocity depends on composition, porosity, degree of alteration, and jointing. Generally we do not expect to produce large quantities of water from bedrock except from joint systems. These can be recognised by a change in velocity in the bedrock. Often large quantities of water may be produced from limestone, but there is no simple relation between the porosity and seismic velocity in limestones (Wyllie, Gregory & Gardner, 1956).

Table 3 shows that some of the velocities in weathered bedrock overlap the velocities in alluvium; therefore it is impossible to distinguish between these rocks on the basis of velocity alone (see section on gravity, Fig. 5), but the attenuation of seismic waves is less in saturated alluvium than in weathered bedrock (Polak, 1971).

As mentioned above, either refracted or reflected waves can be utilised in hydrological investigation. While the literature gives several examples of application of the refraction method, application of the reflection method so far has been very limited as the shallow reflection technique is subject to special difficulties (Pakiser, Mabey, & Warrick, 1954; Pakiser & Warrick, 1956).

The very limited application of the seismic reflection method in groundwater investigations, so far, is mostly due to the inability of the existing seismic reflection equipment to work at shallow depth and at short distances from the shot. To obtain shallow reflections it is necessary to work with much higher frequencies than those used in oil prospecting. A reflected wave of frequency 30 Hz and velocity 3 km/s has a wavelength of 100 m. The accuracy of reading of arrivals is limited at best to one-quarter of the wavelength and therefore to 25 m. To obtain better accuracy, higher frequencies have to be used. However, higher frequenci are characterised by a higher rate of attenuation. New equipment has to be developed to allow trace stacking and therefore adding of energies from small impulses. The process of stacking will also allow suppresion of the direct and shallow refracted waves. This kind of instrument is being developed by BMR.

In alluvium consisting of separate beds, small differences in seismic velocities between beds exist, and therefore reflections will be produced separately at each velocity discontinuity. Several reflections may occur in one wavelength and these reflections will be superimposed on one another. Some of those reflections will also have undergone phase reversals in places where the lower bed is of lower velocity than the overlying bed. Thus a seismic reflection is not a single event originating from a single lithological interface but an interference pattern from several reflections. This factor will definitely limit the possible definition of interbedded aquifers at any depth.

2.3. GRAVITY AND MAGNETIC METHODS

The gravity and magnetic methods are potential field methods and depend on the natural gravity and magnetic fields due to rocks whose density and/or magnetic susceptibility differs from those of the surrounding rock. Several textbooks deal with these methods (Nettleton, 1971; Bheiner, 1973; Heiland, 1946; Jakosky, 1950; Parasnis, 1962; Dobrin, 1960).

In groundwater studies the gravity and magnetic methods are frequently used to determine the basement relief and basement rock type of an alluvial valley or sedimentary basin where the basement is of higher density or susceptibility than the overlying sediments. The thicker portion of the sediments will be generally characterised by a lower gravity or magnetic field. By measuring these fields and assuming simple models for the structure of the sedimentary basin or alluvial valley, an interpretation of the depth to basement is possible. Potential methods suffer from the problem of ambiguity (Skeels, 1947), which is analogous to the problem of equivalence in resistivity prospecting, because different bodies can produce the same gravity or magnetic field. For this reason the gravity and magnetic methods cam be best used when some existing control (such as a borehole to basement or depth estimate from seismic) is available.

In the gravity method a gravity meter, which uses delicate spring measuring systems and can detect changes of 1 part in 10^8 of the Earth's field, is used to measure relative variations in the gravity field on the Earth's surface. The quantity measured is the acceleration due to gravity in units of 0.001 cm/s^2 or milligals. The Earth's field is of the order of 980 000 milligals. The decrease in gravity is typically less than a few milligals over a small sediment-filled valley but may be 50 milligals or more over larger sedimentary basins. Basement rises will be reflected as local increases in the gravity field. Variations in the gravity field on the surface of the Earth are also caused by distance of the measuring point from the Earth's spin axis (latitude effect), the distance from the centre of the Earth (elevation effect) and velocity and direction of movement on the Earth's surface if the measuring instrument is shipborne or airborne (Eotvos effect). Small tidal variations occur also in the gravity field. Field procedure requires careful levelling and positioning of gravity stations to permit latitude and elevation corrections. The field measurements are corrected for instrument drift and tidal variation by reading the instrument at a base station, roughly every two hours. Corrections can be computed for tidal variation if desired. The field measurements are generally related to a station with a known absolute value of gravity (e.g. one of BMR's Isogal stations). The observed gravity values are reduced to mean sea level by applying an elevation correction and a correction for a plate of uniform density and thickness equal to the elevation of the gravity station. Corrections for variation of latitude are also made. The textbooks cited give a full description of the reduction of results.

Figure 6 shows the results of a gravity survey across a buried valley near Albury NSW. A seismic survey was conducted there and it was impossible to differentiate between the older alluvium and the weathered bedrock on the basis of velocities alone. The gravity dita were then subjected to a computer interpretation, using the bore information, and a complete section throughhthe valley was obtained.

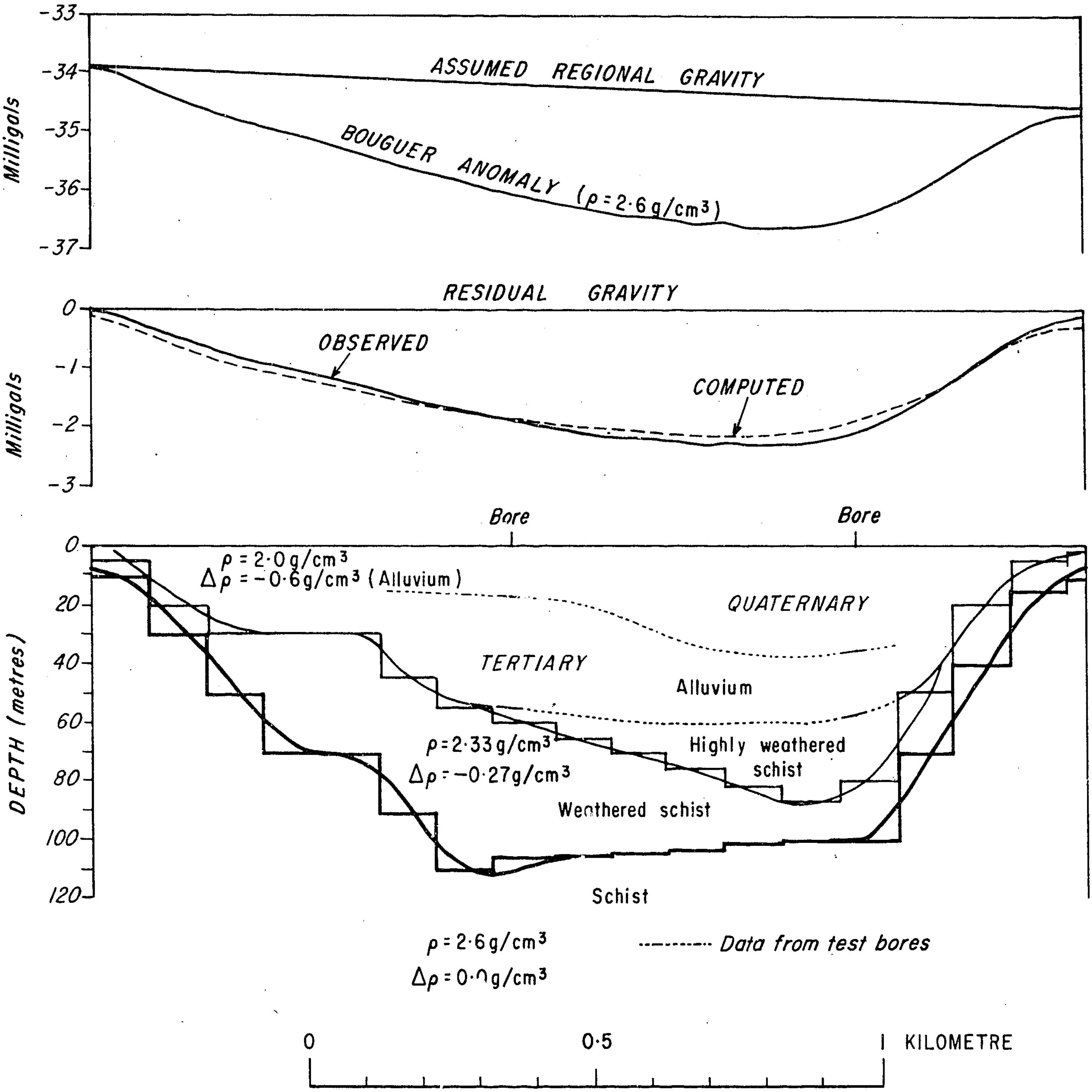
In the magnetic method either the total magnetic field or the vertical component of the field can be measured. The Earth's field in Australia is between 40 000 and 50 000 nanoteslas and inclined between 40^o and 70^o to the horizontal. Rocks of higher susceptibility concentrate the magnetic lines of force and increase the local magnetic field. Sediments are typically non-magnetic whereas basement rocks may have appreciable magnetic susceptibility. Interpretation of the depth to the top of magnetic bodies gives maximum estimates of sediment thickness.

The magnetic method may be useful in delineating shear zones, joint patterns, and directions of dykes in hard-rock environments covered by thin superficial deposits. Weathering processes generally lower the magnetic susceptibility of rocks, and any weathering patterns associated with shear zones or joints will be shown as magnetic lows. Dykes may be represented by either magnetic highs or lows.

Magnetic field measurements are taken either on ground stations or as continuous profiles from aircraft or vehicles. The continuous profile method gives a better detail of the magnetic field and is a much quicker method of data gathering. Corrections must be applied for diurnal variation of the magnetic field due to ionospheric activity. The diurnal changes can be monitored by returning to a base station, as in gravity loop methods, or by a continuously recording magnetometer at a base station. Several parallel profiles are generally used to establish trends of magnetic anomalies.

The magnetic field of a body falls off more rapidly with distance from the body, than the gravity field of the body. Thus the magnetic method is influenced more by shallower features than the gravity method, in which often the gravity anomalies from shallow sources are obscured by anomalies from larger-scale or deep-seated geological features. These properties often prove to be a limitation when applying gravity and magnetic methods.

Fig. 6



DOCTORS POINT GRAVITY PROFILES

3. APPLICATIONS OF GEOPHYSICAL METHODS IN DIFFERENT GROUNDWATER REGIMES

3.1. INTRODUCTION

Table 2 summarises the main groundwater regimes. In Australia the unconsolidated sedimentary deposits and the Great Artesian Basin are the two most important groundwater environments. In these notes, which are in no way complete, some applications and limitations of the various geophysical methods in each of these environments are presented. These notes are based on experience gained from BMR surveys in Australia and Papua New Guinea and information obtained from discussions with Government and private geophysical organisations engaged in similar work. In the oral presentation of this paper numerous case histories are discussed, showing particular interesting aspects of BMR geophysical surveys.

3.2. UNCONSOLIDATED ALLUVIAL REGIMES

This regime is the most common source of groundwater. Two main sub-divisions can be defined:

(1) Inland river vallies

(2) Coastal plains

This regime involves Recent to Tertiary sediments, commonly less than a few hundred metres in thickness, overlying early Tertiary, Mesozoic, or Palaeozoic bedrock. The bedrock may be deeply weathered (deeper than 100 m) but may be of only slightly different density, seismic velocity, resistivity, and magnetic susceptibility from the alluvium. In the case of early Tertiary bedrock, contrasts in properties between bedrock and alluvium may be very small. This is common in areas of rapid deposition (e.g. Papua New Guinea). The alluvial sediments often form complex inter-fingerings and channels of silt, clay, sand, and gravel. An increase in grain-size with depth is common, and basal coarse sand or gravel may be present. Geological correlation is difficult as the alluvium may show marked lateral variation in layering. In coastal areas sea water may intrude the sediments, and connate salt waters, representing old swampland surfaces, may be present.

3.2.1. SEISMIC METHOD

- Provides bedrock and possibly weathered bedrock information
- Weathered bedrock may form a blind zone in seismic refraction. Bedrock determination errors up to 150% have been recorded in extreme cases.
- Generally no subdivision of the alluvial sequence beneath the water-table is possible, but in favourable circumstances thick basal sand or gravel sequences may be defined and narrow buried channels which are limited by old levee banks may show up in the refraction data.
- Depth to perched water-tables obtainable.
- The depth to the main water-table is generally clearly shown and mapping of lateral changes in elevations of the water-table may indicate the direction of groundwater flow.
- Velocity layering and reversals may occur if gravel lenses or old indurated land surfaces are present.
- Layering in alluvium may be shown by shallow reflection. Possible in water-covered areas, but little success reported on land.
- Tertiary bedrock and fluvioglacial bedrock often shows little seismic velocity contrast with alluvium.
- Long shot offsets, generally 3 to 10 times depth, required for bedrock refractions to be recorded.
- Narrow and deep valleys may be indicated as much shallower because of the possibility of refractions coming from the sides.

3.2.2. RESISTIVITY METHOD

- Provides subdivision of alluvium into several layers.
- Sensitive to lateral changes of lithology and resistivity, particularly near-surface variation.
- For routine interpretation layered geometries are assumed. The validity of this assumption is a limiting factor. The tripotential method enables this assumption to be tested; however additional field effort and considerable experience in interpretation is required (Habberjam & Watkins, 1967).
- Difficulties in obtaining unique interpretations due to principle of equivalence. Errors in depth determination of boundaries of layers are commonly 50-200% (Kunetz, 1966).

- Suppression of intermediate layers common where resistivity contrast exists between surface layers and bedrock (e.g. suppression of weathered bedrock layer in resistive bedrock areas).
- Transverse resistance, T, determination is the only reliably accurate parameter obtainable with conductive basement.
- Longitudinal conductance, S, determination possible with resistive basement.
- Deep lateritic weathering with high-resistivity surface layers and conductive basement is common in northern Australia (Pettifer et al., 1974).
- Problems with detectability of thin layers.
- Conductive surface layers are present in some irrigated areas (Polak & Ramsay, 1974).
- Difficulties in establishing a relation between interpreted layer resistivities and lithology due to errors of interpretation and the presence of clay (Pettifer & Taylor, 1973).
- Clay resistivities are high in fresh waters (100 ohm-metres). Much lower resistivities common in normal groundwaters (20-80 ohm-metres). Clays are extremely conductive in areas of seawater intrusion (less than 5 ohm-metres) and brackish groundwaters.
- Electrode expansion of 10-30 times the depth often required to penetrate highly conductive or resistive layers (Kunetz, 1966).

3.2.3. ELECTROMAGNETIC METHODS

- Favoured in areas of high surface resistivity where contact is difficult to obtain. Popular in India where intensive land use inhibits resistivity sounding operations (Patra, 1970)
- EM sounding not used in Australia principally because of predominance of low-resistivity surface layers and ease of use of resistivity sounding method.
- VLF resistivity measurements using "Radiohm" technique provide quick traversing technique. Excellent for locating saline water bodies (Bishop & Polak, in prep.).

3.2.4. GRAVITY METHODS

- Can be used as a bedrock profiling technique in favourable circumstances.
- Weathered bedrock is often intermediate in density and contributes to gravity anomaly.
- Changes in bedrock may mask anomaly due to the variations in thickness of the alluvium.
- Steep regional gradients may mask anomaly (Pettifer, 1974).
- Best used with borehole nad/or seismic control.
- Useful in deep lead investigation where valley is covered by surface lavas.
- Estimates of total water storage valley fills from gravity data (Eaton & Watkins, 1967) are subject to error and should be treated with caution.

3.2.5. MAGNETIC METHODS

- Bedrock profiling technique in favourable circumstances.
- Magnetic strike may not be parallel to alluvial valley direction.
- Continuous-recording vehicle-borne magnetometer is preferred and speeds up operation.
- Useful for locating old channels filled with magnetic material.
- Depth estimates generally based on assumption of geometry of body (e.g. Peters' half-slope factor varies from 1.2 to 2.0 for dykes depending on the width/depth ratio of the dyke. This has been determined empirically in the airborne section of BMR)
- Complements gravity data where bedrock density and susceptibility changes occur.

3.3. CONSOLIDATED SEDIMENTS

This regime, of which the Great Artesian Basin is the outstanding example in Australia, is characterised by deep-seated aquifers in pre-Tertiary sediments. A considerable amount of groundwater exploration in this type of environment has been carried out by the French in northern Africa (Mathiez & Huot, 1966).

The aquifers in these environments are often relatively thin with respect to their depth, and this poses real problems of detection and resolution. Generally indirect techniques are applied in this type of groundwater search. Often thick marker sequences are traced to provide data on structural changes in the groundwater basin sediments. In most of the sedimentary basins of Australia oil exploration data is readily available and aids structural interpretation. Because of the enormous scale and expense of these large-scale groundwater investigations, all available oil search geophysical, drilling, and logging data should be first re-interpreted to assist in planning the groundwater exploration and to provide control.

3.3.1. SEISMIC METHOD

- Necessarily expensive and should only be used to fill gaps in previous data.
- Seismic reflection method most favoured.

3.3.2. RESISTIVITY METHOD

- Deep soundings require high-powered transmitter and sensitive receiving equipment. Logistic problems also.
- Dipole methods most favoured for large expansions.
- Low resistivities (commonly less than 10 ohm-metres) common in the sedimentary section. Limits penetration. (Polak & Ramsay, in prep.).
- Synthesis of electrical sounding curves from laterolog or long normal logs from existing neighbouring oil wells is desirable to provide control. Compare synthesised sounding with field sounding data obtained at the well also. Ghosh Filter (Ghosh, 1971b).
- Method favoured as the number of layers is no serious limitation
- Lateral changes of resistivity in layers not generally as serious a problem as in unconsolidated environments.
- Problems with dipping layers, large structural relief.
- Best used in conjunction with magneto-telluric sounding (Whiteley & Pollard, 1971).

3.3.3. MAGNETO-TELLURIC SOUNDINGS

- Provides information on deeper part of the sedimentary section where penetration of resistivity soundings limited by practical considerations.
- Best used with additional control (seismic, gravity, boreholes, etc.).
- Problems with equivalence of interpretations as in d.c. resistivity soundings.
- Limited resolution of resistivity of resistive layers.
- Sensitive to high conductivity rather than high resistivity (as in all EM methods).
- In favourable circumstances 2-D interpretations possible.

3.3.4. GRAVITY METHOD

- Ideal for providing basement and infra-basin structural relief.
- Best used with aeromagnetic data and seismic and borehole control.
- Cheap and readily available data coverage.
- Heighting errors are less significant, so barometric levelling can often be used.

3.3.5. MAGNETIC METHOD

- Structural relief of basement and infra-basement rock type changes.
- Identifies infra-basin volcanics.
- Best used in conjunction with gravity data and basement reflection data.
- Vehicle-borne magnetometer follow-up of aeromagnetics may be desirable to provide more detailed coverage.

3.4. KARST ENVIRONMENTS

Although a karst environment is common in eastern and southern Australian Devonian limestones, there has been very little investigation for groundwater in these areas. Geophysical work on groundwater in limestone was discussed at this meeting by D.L. Rowston. Considerable effort has been applied on research into karst areas of Yugoslavia, Central Europe, USA, and India, but the work is far from complete and the possibilities of application of geophysics to a karst environment are still to be explored.

BMR is involved in the search for water in a fully developed karst on Christmas Island. The karst is characterised by the occurrence of groundwater in solution cavities, joints, and fissures. Often they are irregularly placed, they may be connected or unconnected, and they may form a major groundwater flow system which may drain the whole area through one or more flows. The geophysics is designed to define these major flow patterns.

3.4.1. RESISTIVITY METHOD

- May determine the depth to the water-table in karstified limestone.
- May define thickness of the karstified limestone (Astier, 1971).
- Resistivity anisotropy determination by the use of circular sounding may indicate the direction of karstification.
- A cavity above the water-table is of high resistivity and may be located by constant-spacing profiling.
- A cavity below the water-table and in solid limestone is of lower resistivity and therefore may be located.
- A cavity route between two boreholes may be located by placing a current electrode in the borehole and moving an assembly of potential electrodes along the second borehole.
- Resistivity sounding and traversing may reveal a cavity located at a depth of 1.5 times the diameter of the cavity.
- The I.P. method may define cavities if they are filled in with mud containing pyrites.

3.4.2. SEISMIC METHOD

- Generally will not indicate the boundaries between the karstified and solid limestone.
- Has been used in locating cavities by exciting resonance of the cavity. Transverse waves may locate cavities providing the limestone is overlying a higher-velocity refractor. The seismic reflection method may locate cavities.

3.4.3. MAGNETIC METHOD

- May locate cavities if they follow a shear zone continuing in underlying rock.
- May indicate cavities if the limestone is of higher susceptibility.
- May indicate cavities if the mud contains magnetic materials.

3.4.4. GRAVITY METHOD

- The gravity method has been used to locate cavities at shallow depth. Generally the method is successful if the weathering is uniform and the terrain level.

3.4.5. EXTENSION OF CAVITIES

Several geophysical methods have been used to plot extensions of the cavities.

- Resistivity method, mise a la masse techniques have been used to follow the flow of salt solutions through cavities.
- Seismic method of direct transmission of the vibration from a blast of explosive charge travelling down the cavity.
- Direct transmission of radio wave from a floating radio transmitter may indicate continuity of a cavity.

3.5. VOLCANIC ENVIRONMENTS

This environment is most important in the Darling Downs area of Queensland and also on Norfolk Island. Very little work has been carried out by BMR in this environment, but considerable work has been done in Hawaii by the US Geological Survey and universities.

The environment is characterised by predominance of fracture permeability along and across the lava flows. Porosity exists in interbedded tuffs, but clays may limit permeability. Often aquifers may form in one particular flow, which may be thin with respect to its depth of burial.

3.5.1. SEISMIC METHOD

- Information on depth of weathering.
- Problems with differential weathering of successive flows and interbedded tuffs producing velocity reversals.
- Lateral variation in velocity may indicate variations in vertical jointing.

3.5.2. RESISTIVITY METHOD

- Generally low surface resistivity and high resistivities at depth.
- Traversing can provide information on depth of weathering and vertical jointing.
- Problems of resolution of thin aquifers

3.5.3. GRAVITY METHOD

- Not readily suited to this environment.
- Detailed gravity may provide depth of weathering in suitable circumstances.

3.5.4. MAGNETIC METHOD

- Detailed vehicle-borne magnetics useful for depth of weathering and indication of vertical joints, dykes, etc.

3.6. METAMORPHIC ENVIRONMENT

This environment is most common in Archaean shield areas of Australia. Because of the remoteness of these areas little demand for groundwater occurs. The techniques for exploration are similar to conventional metalliferous geophysical techniques, and are readily adapted to all hard-rock environments.

Groundwater accumulation is again governed by fractures, shears, and jointing, and is often associated with mineralised zones. Often superficial cover is present.

3.6.1. SEISMIC METHOD

- Information on weathering, jointing, and major zones of shears in bedrock.
- Major exploration tool in this environment. Recommended with resistivity traversing.

3.6.2. ELECTRICAL METHODS

- Traversing methods ideal for location of zones of vertical fracturing or shears.
- Sounding methods of limited usefulness.
- Electrical methods generally restricted to "anomaly finding" techniques. Quantitative interpretation generally not attempted owing to complexities of geology.
- I.P. methods useful for detailed investigations.

3.6.3. ELECTROMAGNETIC METHODS

- Turam, Slingram, EM gun, and VLF techniques are useful for detection of conductive zones.
- VLF resistivity traversing (Radiohm technique) ideal; often can replace more time-consuming gradient array measurements. Conductive zones with strike towards North West Cape Naval Station show maximum coupling with VLF signal.
- Problems with terrain effects in EM.

3.6.4. GRAVITY METHODS

- Not ideally suited to this regime except in areas of surficial cover.

3.6.5. MAGNETIC METHODS

- Ideal for structural information, particularly with parallel traverses across strike with vehicle-borne magnetometer.
- Quantitative information on dip of magnetic bodies possible.

4. CONCLUSIONS

Geophysical methods judiciously applied, bearing in mind the limitations, find ready application to groundwater studies. The geophysical methods are best used with drilling control and continuous geological assessment.

Developments in computer technology have revolutionised interpretation and data processing techniques. The two most promising developments in groundwater studies are improvements in seismic reflection and refraction data gathering and enhancement techniques using digital technology, and the possibility of utilising EM sounding techniques in the field coupled to vehicle-mounted computers to provide rapid electrical sounding information.

Considerable experience in groundwater geophysics has been accumulated throughout the years by BMR, and the authors know this to be true for other government and private organisations also. Hopefully symposia such as this will enable interchange of these experiences and ensure that they eventually reach practising geophysicists in Australia. There is a particular need for more case histories of groundwater geophysical surveys in Australia to be published.

DISCUSSION

Discussion on paper by G.R. Pettifer & E.J. Polak

R.Gerdes (SA Dept of Mines)

Have you any glauconite in the sands and clays at the southern end of the Stock Route magnetic traverse where a magnetic high is indicated?

E.J. Polak

No glauconite was found in three samples investigated.

Mr Crawford (Darling Downs College of Advanced Education)

Have you investigated that you have ferrugenous sands perhaps containing maghemite?

E.J. Polak

Yes, but no maghemite was found.

J. Odins (NSW Water Conservation & Irrigation Commission)

Perhaps there is just a change in magnetisation of the bedrock.

E.J. Polak

The anomalies are too sharp to come from bedrock at a depth of 30 to 60 m. We intend to take oriented samples to prove the magnetisation pattern.

J. Odins (NSW Water Conservation & Irrigation Commission)

Just a quick discussion on the gravity and magnetics. The gravity method is in some respects simpler because you haven't these additional factors to worry you. It is basically a density contrast problem whereas with the magnetics you have not only susceptibility contrasts but also the direction of magnetisation.

E.J. Polak

I agree; however if the magnetic method is viable it is a much cheaper method than gravity.

J. Odins (NSW Water Conservation & Irrigation Commission)

. remember a BMR Record dealing with the micromagnetic method and it suggested that different rock types had different magnetic signatures. By taking readings on a very small grid, direction of jointing could be determined.

E.J. Polak

Yes. This method was used on the Great Lake survey in Tasmania. It was necessary to determine the jointing pattern in dolerite. The measurements were taken on a 3-m grid, contoured, and a rosette was plotted from the direction of contour lines. The rosette tended to indicate the direction of jointing. We took similar measurements on a dam site in Papua New Guinea, where we found that the direction of contours was parallel to the direction of dykes intruding the bedrock.

Mr Crawford (Darling Downs CAE)

I was very pleased to hear you talk about integrated techniques and especially graphical ones. I feel that whilst the computer methods produce more sophisticated and hopefully more accurate results there is still a real need for analysis of the data in the field. One needs to assess the data as it is being collected and perhaps modify the procedure in the field.

E.J. Polak

It is now possible to calculate resistivity curves in the field using small programmable calculators such as the HP65. The other techniques, however, are very important because, as I mentioned before, you may have a field curve which may be distorted and it is very difficult to be corrected. Providing geological control is good enough, the curves may be grouped by the geophysicist and the interpretation carried out by untrained personnel using the Tagg method on a desk calculator. I found the method to be very satisfactory; the accuracy of interpretation was very high. With the resistivity depth probes on a 30-m grid, visual comparison of the field curves could indicate the change in depth from one place to the next. The cumulative method of Moore was also used; in a glacial drift area the point of inflection indicated the edge of a buried channel.

Mr Crawford (Darling Downs CAE)

When you have discovered discrepancies, have you not gone back to see whether these are due to lateral inhomogeneities?

E.J. Polak

The main source of discrepancies between geological and geophysical boundaries was the fresh water invading the porous sandstones in the bedrock. The geological boundary was different from the electrical, as shown by the S-P and resistivity logs.

R. Gerdes (SA Department of Mines)

Referring to the Cape York Peninsula example, where you showed the aquifer and non-aquifer case. Did you try using the tripotential method and determining or plotting the lateral deviations on each electrode expansion as a means of showing where the aquifer was?

G.R. Pettifer

We did not try the tripotential technique because when you have this type of buried channel deposit, and you don't know where the channel is, the problem is the location of the depth probe with respect to the centre of the channel. In this case the channels were aligned east-west, and the direction of our soundings was aligned north-south. The actual detailed cross-section of these channels as in all alluvial channels is generally quite complex and irregular, because of their narrow width, and you virtually have to get right in the centre of these to have anything approaching a layered situation.

One of the problems in using the tripotential method is the variation in surface resistivity - you may remember the example I showed in the talk. We felt in this case the problem was due to the variation in surface resistivity. The variations in surface resistance between the three measuring dipoles in the Wenner array detected differences which we attributed purely to surface variations in resistivity. It is often difficult to determine whether a natural inhomogeneity affecting the curve is at the surface or at depth; for instance, a gradual change in a surface layer may show up as something indicated at depth. We have only experimented with this technique. There would be a need to investigate the behaviour of the Wenner tripotential technique over for instance a cylinder and also to investigate how the response of the array varies with respect to orientation of the array.

R. Gerdes (SA Department of Mines)

Didn't Watkins investigate this in his PhD thesis?

G.R. Pettifer

I am not familiar with Watkins's thesis so I cannot answer that. The natural changes in surface resistivity of the bauxite were enormous in this particular area - one could traverse 20 metres and find a change in surface resistivity from 1000 up to as high as 15,000 ohm-metres. In many cases the lateral changes were more significant that the vertical changes.

N.P. Merrick (NSW Water Conservation & Irrigation Commission)

I should like to make a few comments on the suggestions of using empirical methods in interpretation of resistivity and also of using or plotting resistivity on a linear scale. Theoretically, there is no basis for either method. There are several publications pointing it out. Recently Stewart Greenhalgh of the Department of Main Roads, NSW, investigated these empirical methods. He used published type-curves to work from. He applied empirical methods to these type-curves but found no correlation between empirical interpretation and the theoretical models from which the type-curves were derived. Secondly, on the point of linear scale plotted resistivity depth sounding there is no theoretical justification for small inflections. If, for instance, you tried to model a huge number of layers, say 50, the curve will not show small scale features. In fact the curve may be indicative of a small number of layers.

E.J. Polak

I completely agree with the previous speaker's comments; the matter has been discussed several times. But using the sounding method where the electrode positions overlap each other it is possible to determine whether surface effects are causing a small inflection on the sounding curve or the inflections are coming from below. This method is advocated by Jakosky (1950). The mathematical theoretical background of sounding is a simplification, so we may miss the details. By plotting on a logarithmic scale you preserve many advantages, but you may miss on details. Because everybody plotted on the logarithmic scale the inflections have been suppressed. I feel there may be coming a modification to our theory of electric current flow in the ground to account for these small inflections.

N.P. Merrick (NSW Water Conservation & Irrigation Commission)

Do you take readings at linear electrode spacings when you plot on a linear scale?

E.J. Polak

Normally our field readings are spaced logarithmically, but, if we note small inflections we carry out the survey with much closer, linear spacing.

Mr Crawford (Darling Downs CAE)

I would agree, these empirical methods may not have a theoretical basis but in many cases are found to give useful information.

D.E. Leaman TasmanianMDept of Mines)

I would also like to comment on the subject. Often local knowledge techniques as I would call them are quite useful, using perhaps curve comparison, or other empirical methods, and we have to face up to this fact whether we agree on the theoretical basis of these methods or not. This type of qualitative analysis is possible when a lot of data is available. To say there is no theoretical basis I feel is a rather derogatory comment; however, the anomalies are still there.

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APPENDIX A

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