J. Ind. Geophys. Union (April 2014)
v.18, no.2, pp:245-272

Electrical Resistivity(ER), Self Potential (SP), Induced Polarisation (IP), Spectral Induced Polarisation (SIP) and Electrical Resistivity Tomography (ERT) prospection in NGRI for the past 50 years-A Brief Review

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ABSTRACT
Geo-electrical techniques are used extensively to locate hidden targets that are conductive and resistive in nature. Efficacy of various branches of these techniques has been enhanced due to concerted theoretical, laboratory and field studies. Scientists of CSIR-NGRI played a significant role in strengthening technical base of these techniques. An attempt is made through the present review to project importance of various research initiatives, spanning over five decades.

INTRODUCTION

For any technological development in geophysics, we need to have an integrated approach, wherein we use theoretical, laboratory and actual case studies in an interactive mode. In the present review an effort is made to bring in to focus chronological development of research at NGRI, in various facets of electrical techniques.

The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. Electrical resistivity surveys have been used for many decades in hydrogeological, mining, geotechnical and natural resource investigations. More recently, it has been used for environmental surveys also. The resistivity method has its origin in the 1920's due to the work of the Schlumberger brothers. For approximately the next 60 years, for quantitative interpretation, conventional sounding surveys (Koefoed 1979) were normally used. In this method, the centre point of the electrode array remains fixed, but the spacing between the electrodes is increased to obtain more information about the deeper sections of the subsurface. The measured apparent resistivity values are normally plotted on a log-log graph paper. To interpret the data from such a survey, it is normally assumed that the subsurface consists of horizontal layers. In this case, the subsurface resistivity changes only with depth, but does not change in the horizontal direction. A one-dimensional model of the subsurface is used to interpret the measurements. Resistivity values have a much larger range compared to other physical quantities mapped by other geophysical methods. The resistivity of rocks and soils in a survey area can vary by several orders of magnitude. In comparison, density values used by gravity surveys usually change by less than a factor of 2, and seismic velocities usually do not change by more than a factor of 10. This makes the resistivity and other electrical methods very versatile geophysical techniques. Realising the importance of these techniques, concerted research efforts have been made by a group of scientists, sarting from mid 1960s at NGRI under the leadership of Amalendu Roy. Since then a vast knowledge base has been developed at the institute, to help the field scientists in deploying a specific type of recording geometry for solving a specific problem. Experience gained through one to one interaction between theoretical, lab and field geophysicists has resulted in understanding the efficacy and limitations of resistivity technique. We have seen the greatest limitation of the resistivity sounding method is that it does not take into account horizontal changes in the subsurface resistivity. A more accurate model of the subsurface is a two-dimensional (2-D) model where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line. In this case, it is assumed that resistivity does not change in the direction that is perpendicular to the survey line. In many situations, particularly for surveys over elongated geological bodies, this is a reasonable assumption. Efforts are being made to effectively introduce 3-D recording geometry. Similarly for arriving at apt decisions regarding usage of different types of recording configurations, experience has shown that, if your survey is in a noisy area and you need good vertical resolution and you have limited survey time, use the Wenner array. If good horizontal resolution and data coverage is important, and your resistivity meter is sufficiently sensitive and there is good ground contact, use the dipole-dipole array. If you are not sure, or you need both reasonably good horizontal and vertical resolution, use the Wenner-Schlumberger array with overlapping data levels. If you have a system with a limited number of electrodes, the pole-dipole (three-electrode) array with measurements in both the forward and reverse directions might be a viable choice. For surveys with small electrode spacing and good horizontal coverage is required, the pole-pole (two-electrode) array might be a suitable choice.

In the case of Self Potential (SP) Methods, where no subsurface energisation using external artificial source is done, we simply make use of two non-polarisable electrodes for subsurface investigations for mineral detections. It has got extensive applications for massive sulphide investigations. At present, ground water investigations are also carried out using SP.Induced Polarisation (IP) is yet another method where measurements are carried out during 'off time' and this method is extensively used for investigations of 'dissiminated sulphides'.An indirect application of IP includes detecting clay (being ground water indicators) formations that possess relatively high apparent chargeability/polarisability. This is an indirect application of IP for ground water investigations. Spectral Induced Polarisation (SIP) ,where measurements are carried out over a full spectrum both in time domain(TD) and frequency domain(FD) is extensively in use for mineral detection. It is also used for mineral discrimination like graphite and sulphide.

Tomography is yet another significant tool in Electrical Resistivity (ER),Self Potential(SP) and Induced Polarisation (IP). Multi-electrode systems are in use for Tomography application for the investigations of natural resources and for subsurface geological architecture. Tomography studies give better resolution, high accuracy and more precision.

Since the electrical techniques are regularly used by vast number of geoscientists, it is decided to bring out this review article to expose them to research strides made by NGRI scientists in the last 50 years. We believe the exposure would help in better deployment of these techniques and appropriate interpretation of data generated.

THEORETICAL STUDIES

Electrical Resistivity Prospecting (ER)

In Electrical Resistivity (ER) prospecting, around 1967 or even earlier, the two most widely used electrode systems were those of Wenner and Schlumberger in direct current resistivity profiling/sounding on ground for sub-surface investigations. Apparao and Roy (1969, 1971) began some model experimentation in the resistivity profiling methods across conductive vein type of targets, one of the objectives of which was to compare the performance of the various electrode systems in regard to the amplitude and the shape of their response and their depth of detection. In particular, they were on a look out for an electrode system that would be capable of deeper detection. Obviously, they chose to borrow the idea of focusing the current down into the target in a fashion akin to that in Schlumberger laterolog-7/ surface laterolog on the ground surface for conducting vein type of deposits. This focusing system uses three-electrodes of the same polarity for potential .This ensures passing of a particular quantum of current in to sub surface (Doll,1951). The response of the focused surface laterolog system using seven electrodes, for conducting as well as resistive targets, is equivalent or nearly equivalent to that of the modified unipole having only three electrodes, which in turn can be computed from simple two-electrode measurements. Thus focusing the current down towards the target does not necessarily improve the response measured on the ground surface (Roy, 1975).

As far as conducting vein-shaped targets are concerned, the simplest unfocused two-electrode array has overwhelming response like the unipole, modified unipole and the surface laterolog in shape and amplitude of anomalies, in depth of detection and in cost of operation. For resistive targets, no one system seems distinctly better than the other, except for cost of operations which would be lowest for the two-electrode array.

Excellent theoretical studies in electrical resistivity were carried out over dyke like targets with different transition parameters (Rakesh Kumar,1973).

Studies were carried out to find out the efficacy of one array over the other one using physical model studies. In comparison with the dipole-array, the two electrode array, spacing to spacing (L), gives again better response with regard to amplitude and shape of anomaly, depth of detection and cost of operation. But, if the spacing (L) between the farthest moving active electrodes in an array is not considered as a yardstick for comparison, and the availability of the source power is not a problem in the field, then the dipole array appears better in shape and amplitude. It requires less cable and does not need the infinite cable lay-out. Figure 1 illustrates the efficacies of conventional electrode arrays in resistivity prospecting. Such studies are carried out by defferent researchers (Apparao et al 1978 and Padmavathi Devi et al 2014). A similar systematic study has been carried out in Induced Polarisation (IP) also (Apparao et al 2018) using physical model experimentation .The objective is to have in-depth understanding of the advantages and disadvantages of various conventional electrode arrays both in resistivity and IP.

Depth of investigation by employing particular electrode array has been defined (Roy and Apparao,1971) as that depth of a thin horizontal layer of a homogeneous ground which contributes the maximum to the total signal measured on the ground surface. They further suggested that the depths of investigations computed for all arrays for homogeneous ground can be usefully applied for inhomogeneous situations also. The two-electrode array is found to have the largest depth of investigation. The theoretical analysis on depths of investigation of different electrode arrays has once again brought out the superiority of the two-electrode array over the others; even focused systems. However, the advantage of the two-electrode array in having a higher depth of investigation is counter balanced by its low vertical resolution. Figure 2 shows the depth investigation characteristic curves for various electrode configurations as suggested by

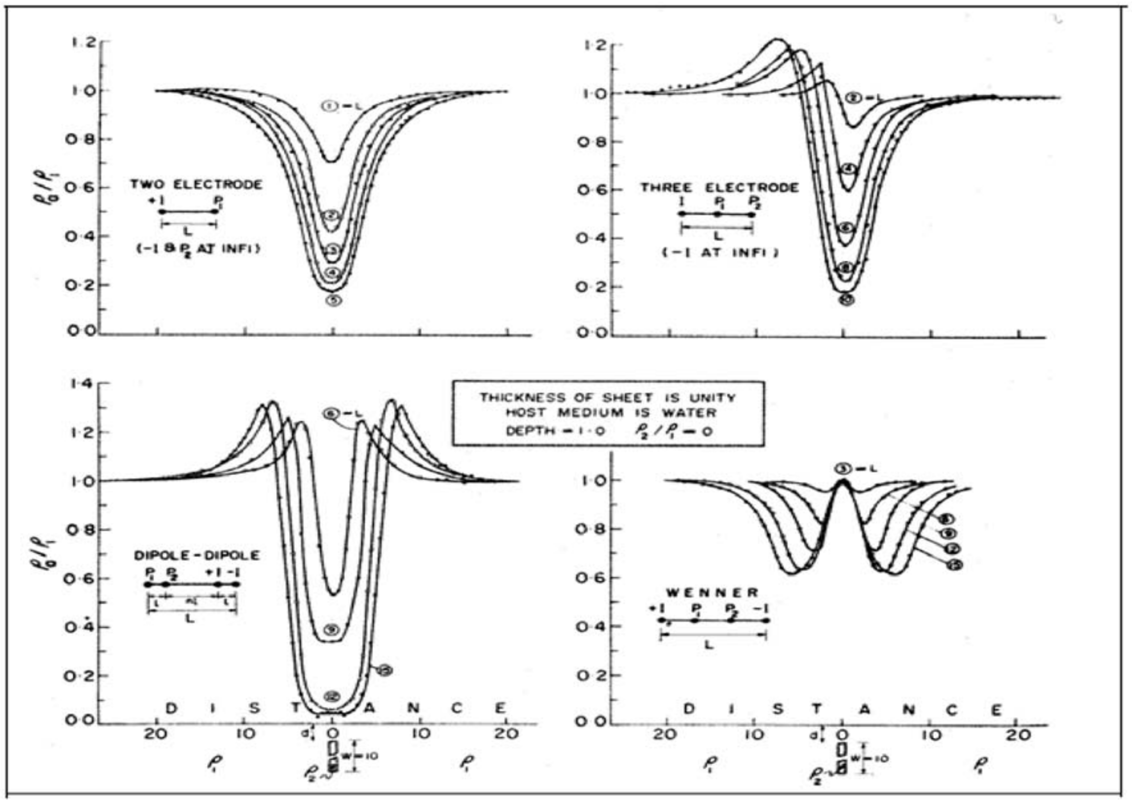


Figure 1. Model tank apparent resistivity profiles with different electrode arrays over metallic target (After Apparao et al 1978)

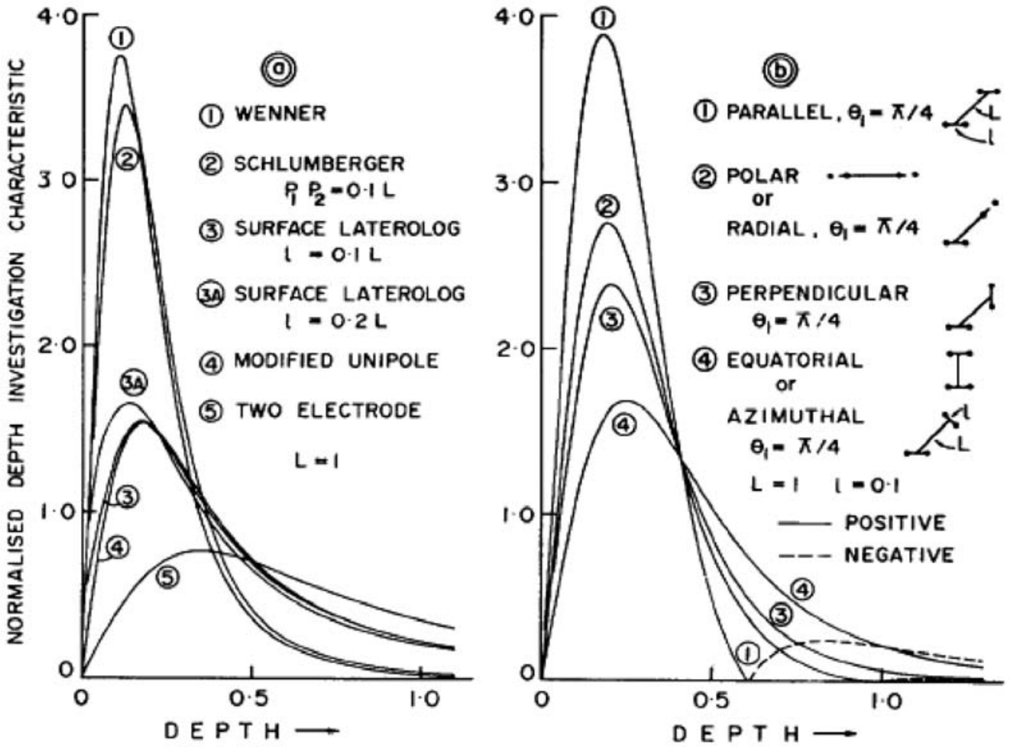


Figure 2. Depth Investigation Characteristics: (a) Wenner, Schlumberger, surface laterolong, modified unipole and Two electrode arrays (b) Some dipole arrangements including polar and equatorial arrays (Roy and Apparao,1971)

Roy and Apparao (1971). Table I presents the depth of investigation values for the conventional arrays.

TABLE I

(1)	Two electrode	0.35L
(2)	Equatorial or azimuthal dipole ($\theta_1=\pi/4$)	0.25L
(3)	Perpendiclar dipole ($\theta_1=\pi/4$)	0.20L
(4)	Polar or radial dipole ($\theta_1=\pi/4$)	0.195L
(5)	Parallel dipole ($\theta_1=\pi/4$)	0.18L
(6)	Modified unipole	0.18L
(7)	Surface laterolog (O_1O_2 = 0.1L)	0.17L
(8)	Surface laterolog (O_1O_2 = 0.2L)	0.135L
(9)	Schlumberger	0.125L
(10)	Wenner	0.11L

It is matter of intuition that a buried target at the depth of investigation of an electrode array gives more response on the ground surface than when the target is above or below that depth. A modified pseudo-depth section was suggested by Apparao and Sarma (1982) to obtain by plotting the apparent resistivity and/or apparent polarisability values at the maximum contribution depth of investigation of the array. Following the maximum contribution concept, an empirical method of constructing pseudo-depth section with any electrode array over an anomaly zone is suggested in IP and/or resistivity prospecting. Model and field studies show that the maximum anomaly contours, in the pseudo sections thus made, tend to close up right over the target cross section. This observation has an important bearing in mineral exploration. It facilitates one to locate the target beneath the ground surface directly in the field survey. The Depth of investigation values over conductive sheet like targets with different electrode configurations (Apparao et al 1997 a) are given in the Table II.

As a sequel to this work, Sarma et al(2001) also have proposed the depth of investigation for dipping dyke models with different electrode arrays as 0.5 times the depth of investigation of the array for homogeneous ground. The multiplication factor 0.5 holds good for all sheet models irrespective of the inclination.

Following the above theory of depth of investigation proposed by Roy and Appa Rao in 1971, Edwards (1977) suggested a modified pseudo section which is, however, based on median depth of investigation. Ample illustrations are made to show that the former pseudo sections basing on maximum contribution concept are far superior to the latter based on median depth in direct location of the target, even though both methods are empirical. The DIC values proposed on maximum contribution concept and on median depth of investigation are shown in the Table III.

Model and field studies demonstrate that the pseudo-depth section serves as a convenient tool in prospecting for conducting minerals and in the location of the boreholes. Figure 3 illustrates the Modified pseudo-depth sections constructed by physical model data over a conducting sheet-like target submerged in different orientations, which ultimately helps to interpret the true geological disposition of the target. The tool was successfully tested in a virgin area at Jonnagiri of Andhra Pradesh for resistivity and IP studies (Figure 4). The field investigations yielded very interesting results.

TABLE II. Summery of depths of investigations over sheet targets at different inclinations buried in an otherwise homogeneous medium

Array	Depth of Investigation (DI)								
	Hor. Res. Sheet θ = 0°			Inc. Res. Sheet θ = 30°			Inc. Res. Sheet θ = 60°		
	d	L_{max}	DI	d	L_{max}	DI	d	L_{max}	DI
Wenner (DI for homogeneous ground 0.111 L	0.50 t	10.1 t	0.050	0.50 t	0.0 t	0.050	0.50 t	9.8 t	0.051
	0.75 t	13.0 t	0.057	0.75 t	14.0 t	0.054	0.75 t	12.6 t	0.059
	1.00 t	15.9 t	0.062	1.00 t	16.0 t	0.062	1.00 t	16.2 t	0.062
Dipole-dipole (β-Wenner) (DI for homogeneous ground 0.101 L	0.50 t	10.2 t	0.049	0.50 t	10.5 t	0.048	0.50 t	10.1 t	0.050
	0.75 t	14.0 t	0.053	0.75 t	15.1 t	0.050	0.75 t	15.1 t	0.050
	1.00 t	15.9 t	0.062	1.00 t	17.2 t	0.058	10.00 t	16.5 t	0.060
Three-electrode (DI for homogeneous ground 0.165 L	0.50 t	6.2 t	0.081	0.50 t	6.1 t	0.082	0.50 t	6.1 t	0.082
	0.75 t	9.0 t	0.083	0.75 t	8.9 t	0.084	0.75 t	9.0 t	0.084
	1.00 t	11.2 t	0.089	1.00 t	11.2 t	0.089	1.00 t	11.2 t	0.089

TABLE III

Array	Edward's(1977) Median Depth Of Investigation, Z_{med}/L	Roy And Apparao's (1971) Maximum Contribution Depth Of Investigation, Z_{max}/L
Dipole-Dipole		
N=0.5	0.101	0.066
1.0	0.139	0.101
2.0	0.174	0.130
3.0	0.192	0.147
4.0	0.203	0.155
5.0	0.211	0.162
6.0	0.216	0.167
7.0	0.220	0.170
8.0	0.224	0.173
Wenner	0.173	0.111
Three-Electrode	0.259	0.165
Two-Electrode (Infinity Electrode At 10L)	0.724	0.350

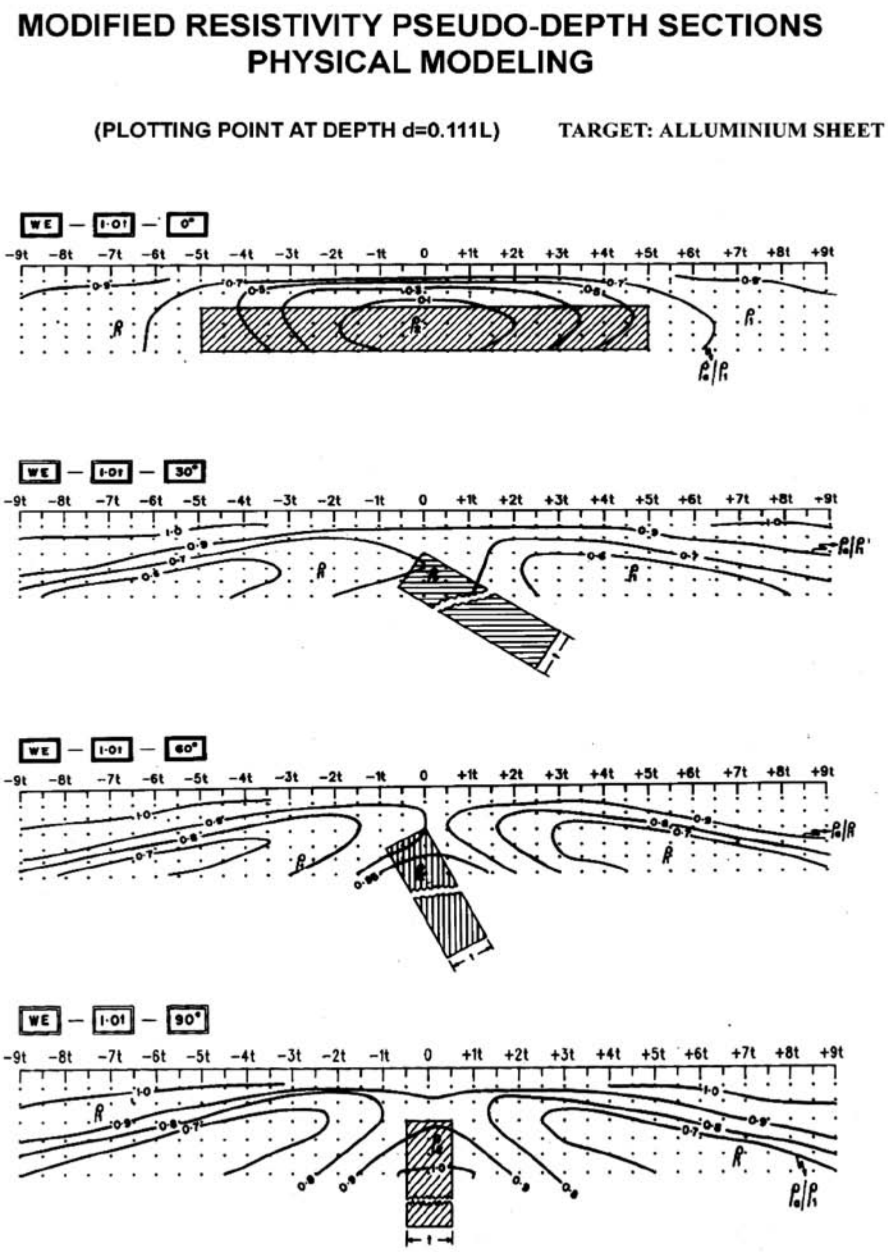


Figure 3. Modified Pseudo-depth sections over conducting target at different orientations with Wenner array. Target depth: 1.0 cm Inclinations: 00, 300, 600, 900 (After Sarma,1982)

Digital Linear Filtering in Interpretation of Resistivity data

a) Bi pole - Dipole method of resistivity sounding

Verma and Das (1979) developed a theory for bipole-dipole method of resistivity sounding. The bipole-dipole apparent resistivities have been shown to be related to that of Schlumberger apparent resistivities, at two spacings. Thus, the bipole-dipole type curves can be computed very fast making use of the filters available to compute the Schlumberger curves. The theory developed can also be used to compute exact dipole - dipole apparent resistivity curves, providing an improvement over the existing techniques which involve far field approximations.

A comparison of bipole - dipole and dipole - dipole systems has revealed the similarity between

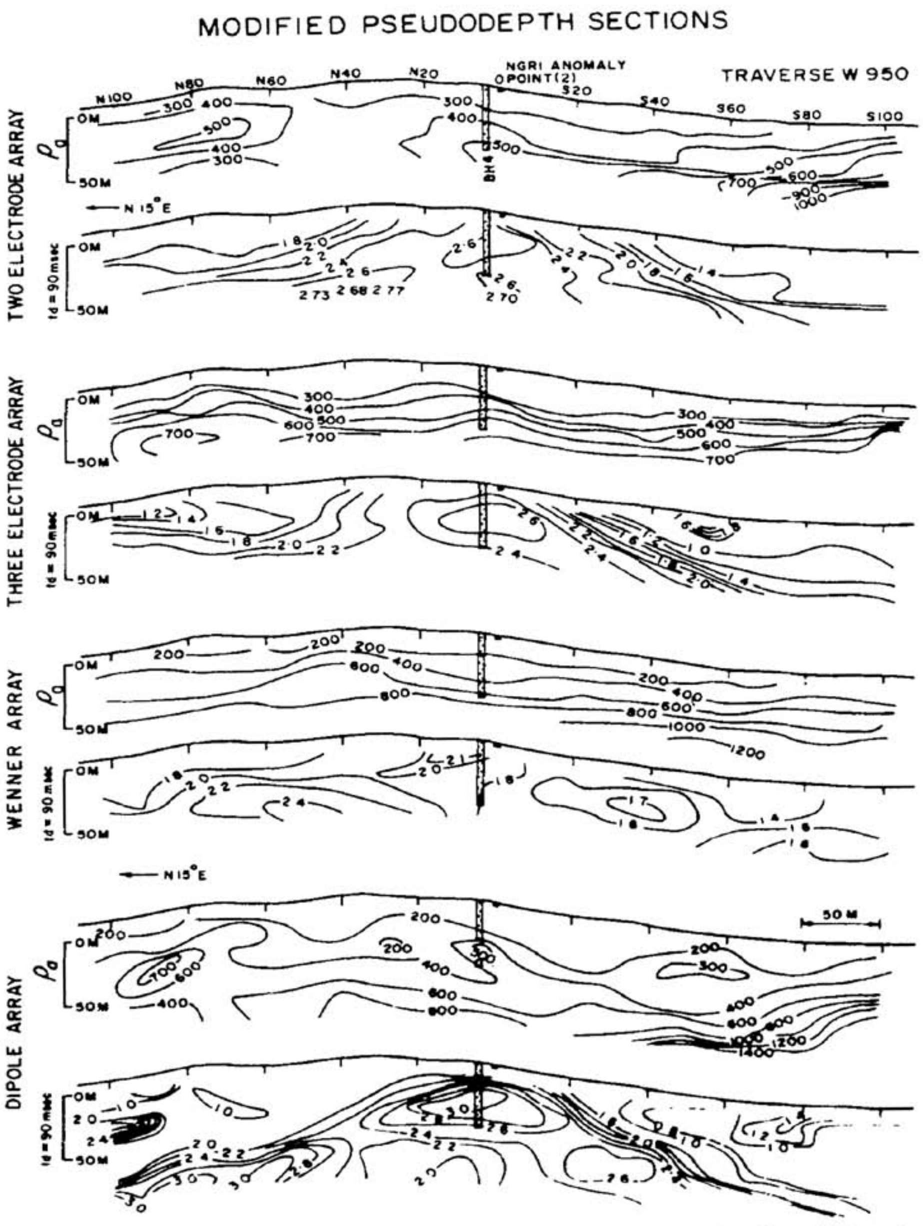


Figure 4. Modified Pseudo Depth sections in IP and Resistivity Studies (After Apparao and Sarma,1983)

the two. However, unlike the latter (excluding parallel configuration) the former has been found to be dependent on the azimuth angle, thus showing varying degree of resolution with it. The versatile nature of the theoretical expressions has led to the proposition of a generalized field scheme independent of the bipolar or dipolar nature of the current source. In addition to their application in ground water surveys, the results obtained would prove to be particularly useful in deep crustal investigations and geothermal explorations.

b) Computing type curves for the two-electrode system of resistivity-sounding

Principle of digital linear filtering has been adopted by Verma and Das (1979) to compute the type curves for the resistivity sounding measurements obtained by the two-electrode system. The filter function required for the purpose has been found to be identical with that used to compute the EM sounding curves for two coplanar horizontal loop system.

Relative performance of the two-electrode system vis-a-vis other configurations has been studied with the help of theoretical and field sounding curves. It has been confirmed that the two-electrode system possesses much (about 5 to 6 times) greater exploration depth as compared to the Wenner and the Schlumberger systems.

Generalized computer program to compute resistivity sounding curves using digital linear filters:

Verma and Das (1979) have developed a generalized computer program to compute the type curves for Wenner, Schlumberger, two-electrode, and dipole - dipole configurations over N-layered earth. A monograph describing the theory of digital linear filtering and its relevance to the computation of resistivity master curves has been prepared by them.

Interactive computer interpretation of resistivity sounding measurements

A computer program, based on the digital linear filtering technique, has been used by Verma and Das (1978b) to plot the theoretical curve on a graphic display terminal connected to PDP-11/40 computer system available at NGRI. On the same display screen the field data can also be easily displayed. To obtain the subsurface layer parameters the theoretical curve is matched with the displayed field curve.
Trial and error adjustments are made to modify the theoretical curve interactively until it yields a satisfactory match with the observed curve. Modification in the model parameters and the display of the finally selected representative model is speeded up by them.

Effect of vertical contact on Wenner soundings

Rakesh and Chowdary (1977) analysed the effects of vertical contact on Wenner resistivity soundings. They showed that two layer resistivity sounding curves will get distorted to three layer sounding curves due to the presence of vertical contact in neighborhood. These distortions would give rise to K or H type of sounding curves over two layered earth. They constructed Wenner resistivity sounding curves on bi-logarithmic paper over simple composite earth models consisting of vertical contact separating two or three layered earth on one side and homogeneous medium on the other side. The error incurred in the graphical construction was explored. Subsequently, they have demonstrated the use of these constructed curves for the interpretation of Wenner sounding curves with the help of two field soundings measured in a geologically complex region.

Azimuthal resistivity profiles over an outcropping vertical dyke

Chowdary (1977) analysed the theoretical resistivity profiles taken at various angles to the strike of the outcropping vertical dyke of infinite depth extent for various parameters like - dyke width, resistivity contrast and electrode spacing with Wenner and two electrode configurations. He showed that inclined profiles taken with Wenner configuration exhibit larger magnitude and broader width compared to the inclined profiles over wide and moderately wide dykes. In case of thin dykes the inclined profiles exhibit reduced magnitude with larger width. He has also shown that the profiles taken at two or three different angles with two electrode configuration, present a point of intersection, which establishes the position of the vertical walls and hence the strike of the body. He concluded that the two electrode inclined profiles provide more information to establish the strike of the body.

Monographs of resistivity profiles over conductive and resistive targets using physical modeling

NGRI has brought out Monographs of resistivity profiles (Apparao et al,1993) and Modified pseudo-depth sections (Apparao et al,1993 and Sarma et al 2007,2008,2009) over conducting and resistive targets of definite geometry which are extensively in use by field geophysicists in Mineral exploration.

Resolution of resistivity anomalies

Resolution of resistivity anomalies is yet another concept that has been studied by NGRI (Apparao et al 1979) using physical model experimentation, which is useful in situation of en 'echelon' distribution of veins below the ground surface. Figure 5 illustrates one such example over conducting multiple targets. This concept has been well continued by Sarma (2001) over conducting targets at different transition parameters.

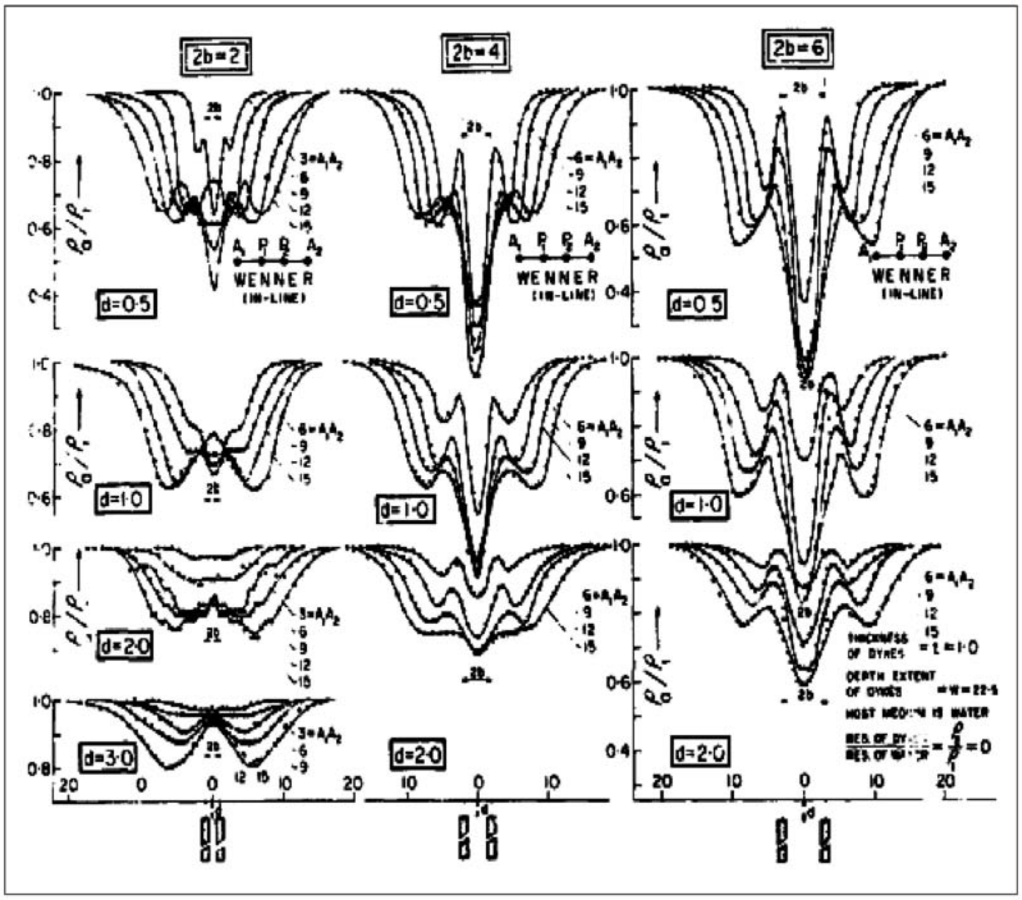


Figure 5. Model tank, Wenner apparent resistivity profiling curves over two vertical infinitely conducting dykes buried at depth d and separated by distance 2b, thickness of the dykes t = 1. (From Apparao, 1979)

INDUCED POLARISATION (IP) STUDIES

Catalogue of IP profiles over an outcropping vein

IP and resistivity master curves have been prepared by Jain and Apparao (1979) over an outcropping two dimensional dyke of arbitrary resistivity and of infinite depth extent using Seigel's (1959) theory for various electrode configurations and spacings. These curves exhibit complicated nature.And as such, their utility has been limited to interpretation of field data; in location of shallow depth-targets.

In-line and Broad-side profiling in resistivity and IP

It is difficult to interpret quantitatively resistivity profiling curves obtained across a single dyke without the help of resistivity master curves. The difficulties become more in case of veins. A detailed model tank study of the response curves for both in-line and broadside profiling with Wenner and Two-electrode arrays showed that the latter array resolves an in-line anomaly much better than the former with same spacing L=3a where `a` is the inter-electrode spacing. In contrast, in broadside profiling the Wenner system is better than the two-electrode in the resolution of the resistivity anomaly. A good amount of work was carried out for finding out efficacies of In-line and Broad side responses over resistive targets. Apparent resistivity sounding curves over vertical sheet with in-line (solid line) and broadside (dashed lines) arrays at various target depths are illustrated in Figure 6. This has got a significance for finding out depths of sub-surface targets (Apparao et al,1997 a).

Depth of Detection as an exploration tool in resistivity and IP

For some reason or the other, it is still not uncommon to find that the term, depth of detection,

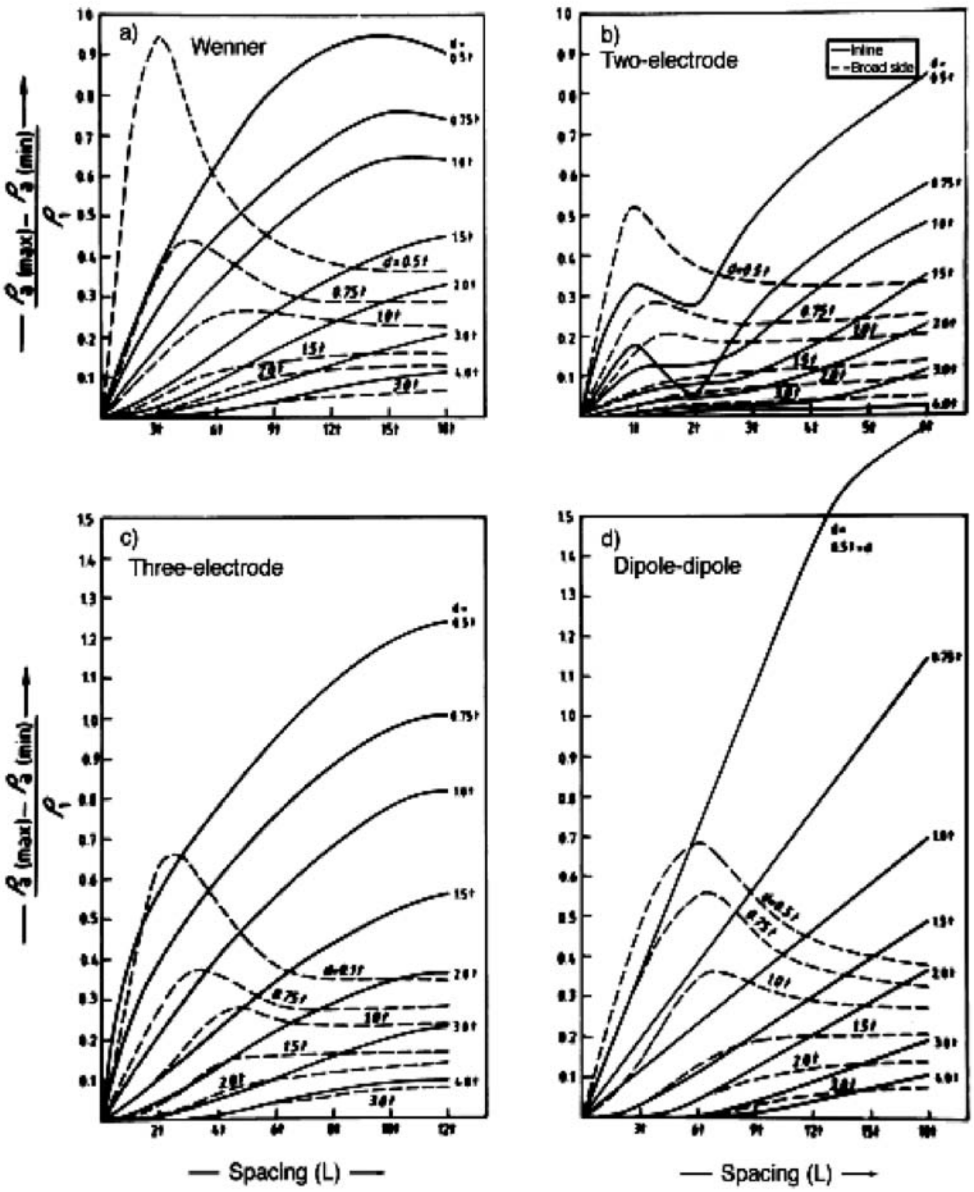


Figure 6. Apparent resistivity sounding curves over vertical sheet with in-line (solid line) and broadside (dashed lines) arrays at various target depths. (After Apparao et al 1996)

is loosely used by field geophysicists for the depth of investigation of an electrode array. They (Apparao and Sarma ,1983) define depth of detection of a target, in resistivity and IP as that depth below which the target cannot be detected with a given array. Following this definition, model experiments with a horizontal cylindrical conducting target, submerged in host medium, water, revealed that the depths of detection to the top of the target with Wenner and two-electrode arrays are 1.5 and 6.0 times the radius of the target below the ground surface, when the depth profiles are taken perpendicular to the strike of the target. This is illustrated in Figure 7. For targets of limited lateral extent the two-electrode array is, on the other hand, seen to be superior to the Wenner array. When all the values of depths of detection of various electrode arrays are presented, it is noticed that the dipole array is found to have greatest depth of detection and the two-electrode array has the least (as far as detection of a sandwiched layer in a horizontally three layered ground is concerned). The Wenner and/or Schlumberger array is found to have depth of detection in between those of dipole and the two electrode arrays.

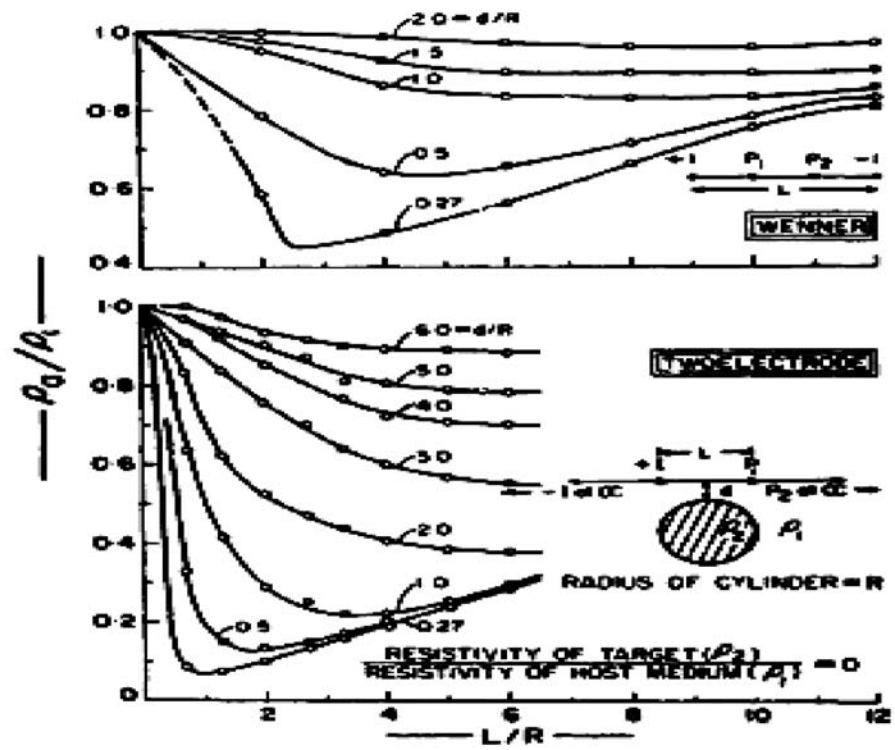


Figure 7. Wenner and two-electrode depth profiles over a buried horizontal infinitely conductive cylinder within the host medium, water, contained in a tank. (From Apparao and Sarma, 1983b,)

Downward continuation in IP

The method of downward continuation is well-known to those working in gravity, magnetic, self-potential and low frequency electromagnetic exploration. It is demonstrated that the method can also be usefully employed in interpretation of induced polarization (IP) gradient profiling using point electrodes to determine target depth. The apparent resistance (Ra) and chargeability (Ma) measurements with point electrode excitation of the ground have been suitably used to compute measurements RaL and MaL that one would obtain with linear array. This geophysical tool was successfully applied (Apparao et al ,1995), as a case study in a Sulphide area in Aladahalli area, Karnataka State. The method of downward continuation has been tested for its application , in a well known sulphide area by using IP gradient profiling data in time domain (using point electrodes for determining depths of 2D conducting targets). The apparent polarisability profile computed for linear array, brings out two IP highs of almost the same magnitude, separated by a low. The two highs fall over the mineralization zone. Further, the IP highs are corroborated by resistivity lows, as illustrated in the Figure 8. Downward continuation of the IP profile has yielded a target depth of 19 meters. A correlation with Bore Hole litholog has suggested presence of disseminated mineralization at this depth.

FIELD STUDIES

Field tests on performance of two-electrode vis-a-vis other arrays in resistivity and IP

Encouraged by earlier model experimental and theoretical results of resistivity profiling over conducting vein by the two-electrode vis-a-vis other configurations, Apparao and Roy (1973) carried out field tests in four areas. Three of these areas had conducting vein-like targets of altered volcanic neck, sulphides and graphite. The remaining area related to a resistive target - a quartz vein intrusive into granite. The field results proved beyond doubt that the simplest unfocused two-electrode array has overwhelming advantages over the Wenner, Schlumberger, modified unipole and focused surface laterolog systems in shape, amplitude of anomalies,

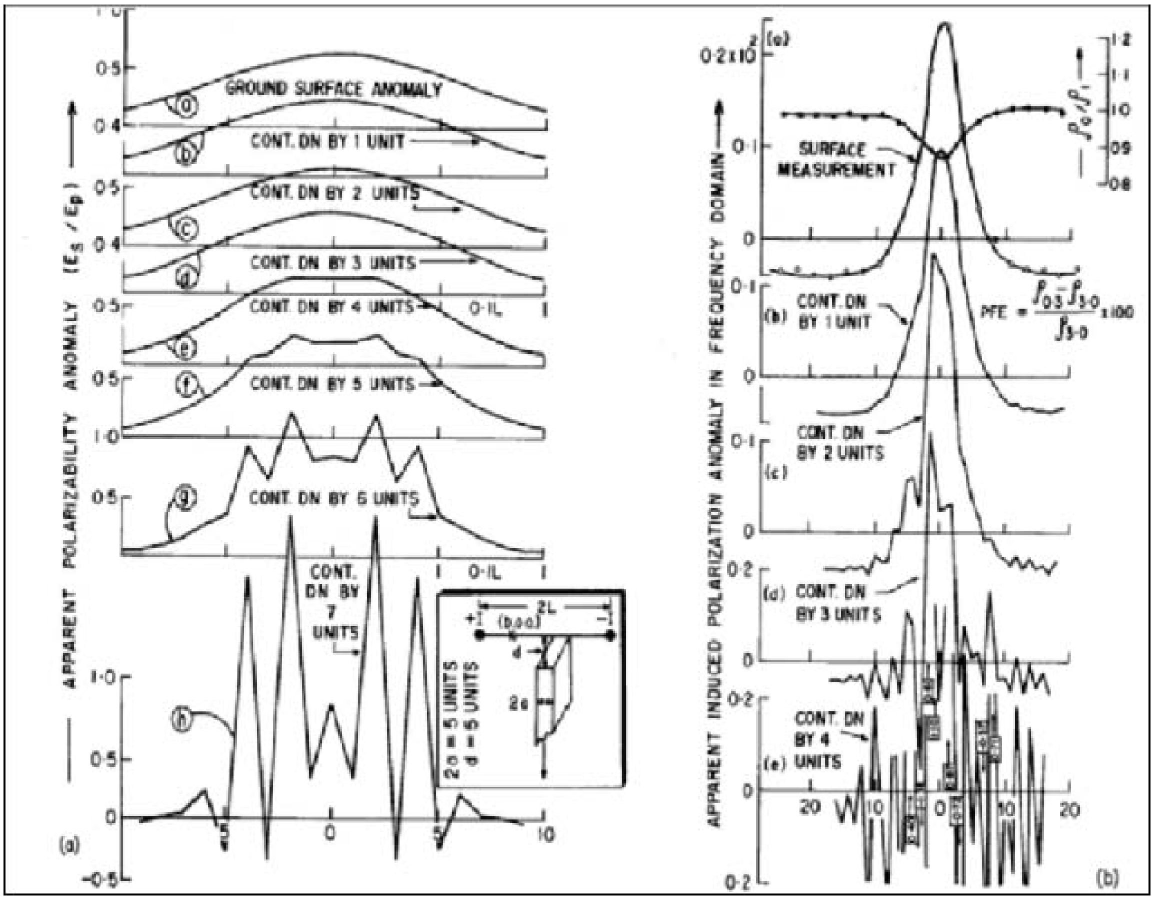


Figure 8. (a) Downward continuation of computed IP profile obtained over infinitely conducting sheet situated at a depth d=0.1L, midway between the two linear electrodes (b) Application of the continuous technique to an experimental surface profile obtained in the frequency domain over a metallic sheet at a depth d=0.5cm. Current is applied through linear electrodes. (After Apparao and Gangadhara Rao,1983)

in depth of detection and in cost of operations. Later Roy and Jain (1973) carried out induced polarisation measurements over the same field traverses of Apparao and Roy (1973) in the sulphide and graphite areas. The electrode systems used in their field studies for comparative performance are: two-electrode, three-electrode, modified unipole, pole-dipole, dipole-dipole, Schlumberger and Wenner (a, and (3). They showed that IP profiling and the simplest two -electrode array produces the largest anomalies with the smallest of spacings.

Experimental resistivity surveys for Bauxite

At the request of the Bharat Aluminium Company Ltd (BALCO) experimental resistivity surveys for bauxite prospecting at Amarkantak (M. P.) were carried out by Sheel C. Jain and Shanker Reddy during early part of 1977. The test resistivity surveys suggested that the bauxite occurrence is not always associated with resistivity high alone, but also at places with resistivity lows. Some of the resistivity soundings showed the presence of a highly conducting bottom layer, possibly due to the presence of lithomarge, as evidenced by its existence in deep boreholes at depths varying from 20 to 30 m.

Feasibility studies with two-electrode array in Jonnagiri for Sulphides

Bhattacharya and Jain (1976) carried out feasibility studies by using two-electrode array to detect relatively deeper ore body by IP and resistivity surveys in Jonnagiri area, Pattikonda Taluk, Kurnool District (A. P.). The Geological Survey of India has carried out earlier by conventional arrays the resistivity and IP prospecting in this area. The GSI has detected two zones of mineralization --zone I and zone II. Drilling results have proved massive pyrite at shallow depth in zone I and drilling in zone II intersected only poor oxidized zone.

The resistivity measurements conducted by NGRI in zone I clearly showed that the two-electrode array can detect the body with much smaller spacing than of conventional array. It was found out that the two-electrode anomaly is not only larger in amplitude but also smoother than the anomalies picked up by the conventional arrays.

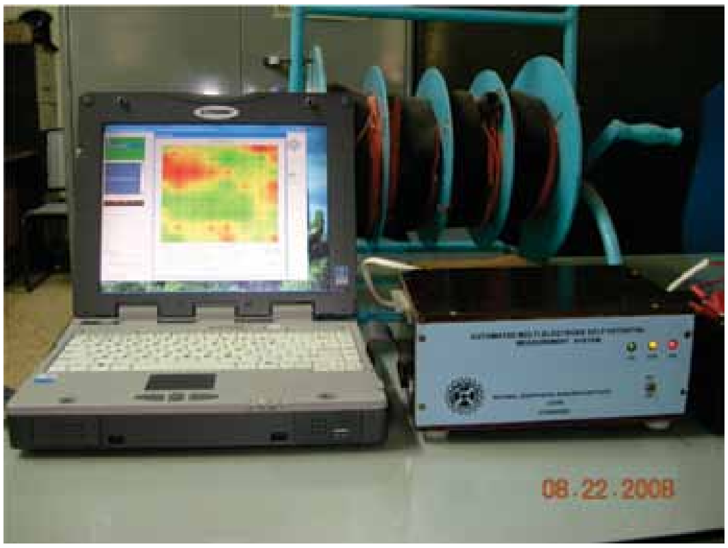
It is a common notion that in induced polarisation surveys, as in resistivity prospecting, the depth of investigation depends on the electrode spacing. The greater the spacing of an electrode array is, the larger is the depth of detection, Apparao, Reddy and Sarma (1978) have shown by illustrations that in IP surveys, the depth of detection depends not only on the electrode spacing, but also on the delay time-the time after the charging current is shut down, when the apparent polarisability is measured.

Modified pseudo-depth section in resistivity and IP

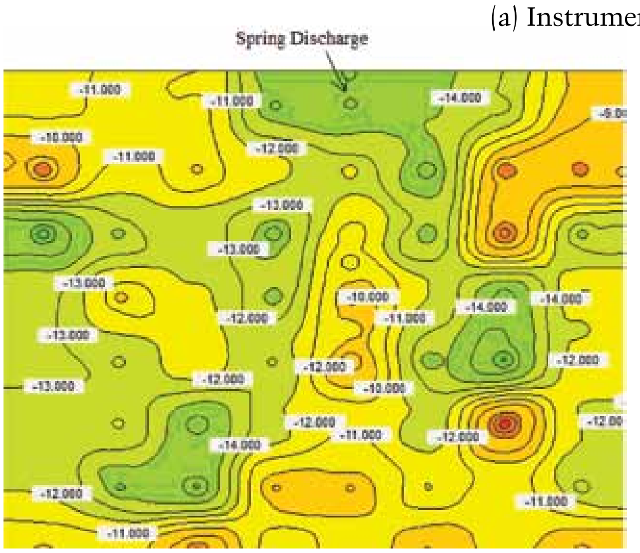
Roy and Apparao (1971) have defined depth of investigation for any array as that depth which contributes maximum to the total signal measured on the ground surface. According to this definition the depths of investigation for different arrays - in case of homogeneous ground are shown in Table 1 on the right hand side. Edwards (1977), while appreciating the physical validity and practical application of the theory of depth of investigation proposed by Roy and Apparao, suggested, however, effective depth of investigation for any array as that depth at which 50% of the total contribution (signal) originates from above and 50% from below. Thus his effective depths for various arrays are also shown in Table 1. He maintains that the median depth of investigation proposed by him appears to be a more suitable measure of effective depth than the maximum depth of investigation proposed by Roy and Apparao (1971). His observation has stimulated Apparao, Reddy and Sarma (1978) to prepare and examine resistivity pseudo depth sections with the model data obtained in the laboratory with metallic sheet as target on the basis of definition of Roy and Apparao. Figure. 6 (a), (b), (c) and (d) show model tank resistivity pseudo-depth sections obtained over the target with host medium water with Wenner, dipole-dipole, three-electrode and two-electrode arrays when the target is horizontal and at depth d=1.0 below the water level. Their study has amply illustrated that the maximum apparent resistivity anomaly contours close up right over the target cross section for any electrode array. From this study it can be concluded that the depth sections help us in finding out the true geological disposition of the anomaly causing target.

Encouraged by these model results, Apparao, Reddy and Sarma (1978) used and re-plotted Edward's field data(published in Geophysics -1977), with dipole-dipole and two-electrode arrays from Monywa Copper Area, upper Burma. Figure. 7(a) is a reproduction of his pseudo-depth sections prepared with profiling cum sounding data in IP (frequency domain) survey over the area. The top metal factor depth section is with dipole-array for n varying from 1 to 6 and dipole lengths a = 25, 50 and 100 meters. The bottom depth section obtained over the same traverse is with two electrode array for spacings ‘a’= 75, 125, 175 and 225 m. For the sake of comparison see Figure. 7(b), which shows pseudo-depth section (top) over the same traverse prepared with the same field data obtained with dipole-array, on the basis of 'maximum' depth of investigation. The bottom section shows that of two-electrode array. One can easily see the pseudo-depth section prepared on the basis of maximum depth of investigation is the best choice either with dipole-dipole or with two-electrode. The maximum anomaly contours close up right near the sulphide mineralization, as evidenced by the three vertical boreholes. The hatched portion down the borehole length represents sulphide mineralisation, the dotted portion represents diabase (host rock). However, when one compares the pseudo-depth sections of dipole-dipole with that of two-electrode (Figure. 7-b), then the dipole array seems to resolve the anomalies much better than the two - electrode array. But, it must be said that the density of field data in two-electrode depth section is much less than in dipole-depth section. The two - electrode depth section has only 5 profiling levels, in contrast to the dipole depth section where 13 profiling levels exist. The density of data plays a vital role in the resolution of anomalies in a vertical section.

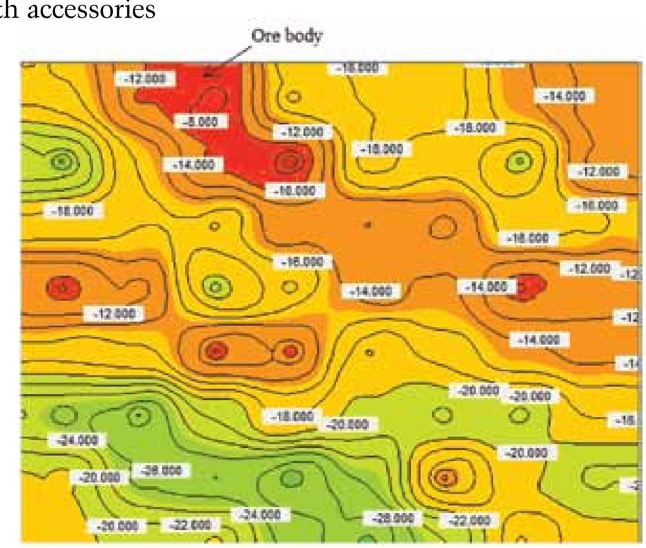
Delineation of groundwater resources in hard rock terrains is one of the important topics to be treated with a more advanced approach than simple one dimensional attitude, particularly when looking for deeper water saturated horizons. In their study, Singh et al (2002) have introduced an integrated geophysical



(a) Instrument with accessories



(b): for groundwater exploration



(c) for mineral exploration

Figure 9. SP Tomography,Instrument and responses for ground water and mineral exploration (Muralidharan et al ,2008)

approach to identify structural features such as fractures, weak zones and intrusive dyke bodies, which can control and host potable groundwater at greater depths. The same group (Singh et al 2000 and 2003) has also carried out Deep resistivity sounding (DRS) studies along the corridors of a N-S trending Kuppam- Palani geotransect, cutting across all the major tectonic blocks in the terrain. Schlumberger electrode configuration was used, since it is less affected by the shallow lateral inhomogeneities. The results yielded useful information and helped in better imaging of sub surface deeper formations, in co-ordination with other geophysical techniques(using an integrated approach).Similar integrated studies have been carried out in trap covered Saurashtra Peninsula and Deccan Syneclise.In all these studies efficacy of DRS has been established.

IP measurements for Arsenic Contamination studies in MGP

Chandra et al., (2011) have carried out an integrated hydrogeophysical study utilising resistivity and induced polarization imaging, in the arsenic affected region of Balia-Patna sector in Middle Ganga Plain. IP measurements were found more responsive to the clay identification than the resistivity. This has lead to an important finding about lithological set up that plays a major role in understanding the arsenic contamination in groundwater. It is noticed from these studies that although alluvial deposits are known for their hydrogeological homogeneity and stratification, the heterogeneities found in stratification close to the river seem to be responsible for arsenic contaminations in patches. The thickness of clay pockets varies and pinching of these pockets seems to play an important role in lithological stratification. To better segregate the layers that have contaminants, from other formations, one needs to carry out high resolution geophysical investigations. The high resolution of electrical resistivity tomography has provided subsurface lithological discontinuities from the surface to even deeper level (say 90 m). The discontinuity of the layer may create leakage from upper aquifer to lower and contaminate the safe zones. Another study has also been carried out in finding out efficacy of electrical resistivity and induced polarization methods for revealing fluoride contaminated groundwater in granite terrain (Nepal Mondal et al 2010). The results have confirmed the effective application of these two methods in pollution studies.

SELF POTENTIAL (SP) STUDIES

Self Potential survey has been carried out along Magnetic survey in Madagaskar area in joint collaboration with National Mineral Development Corporation (NMDC) for primary gold investigations (Mallick et al 1998 and Naqvi et al 1999). Dutta et al., (2006) have mapped the orientation of fractures by preparing a quasi 3D model of electrical resistivity in hard rock terrain. Arora et al, (2007) imaged contaminant plume in landfill of Southern France. They worked on the spontaneous potential "SP" signals and mapped the extent of redox potential generated by the contaminant plume. This is the first work to give the concept of Geo-Batteries, which plays a very important role in unsaturated zone studies. Lind et al., (2007) implemented a hydrogeological modeling code to calculate the SP distribution during primary drainage. They developed 1- D drainage experiment for predicting the SP in vadose zone. The developed technique helps in understanding the process involved for the movement of moisture and characterizing various controlling parameters through unsaturated zone ; a very critical and necessary aspect of hydro-geophysical research.

SP in characterizing the lineaments potential or no-potential for groundwater dynamics

Chandra et al. (2006) studied lineaments such as dolerite dykes and major fractures running along the river/ stream course and showed that lineaments need not contribute always in controlling the ground water dynamics. They have demonstrated that the geophysical characterization helps in better understanding the potentiality. Chandra et al., 2006 showed that the Self Potential is an effective tool to characterize the groundwater potentiality of the lineaments. This was proved through studies in Granitic terrain of Karnataka. It has been shown that identification of the potential lineaments can be made, as they are usually associated with regional lows.

Technology invention for water and mineral prospecting using SP tomography

The main objective of the present invention (Muralidharan et al ,2008) is to provide a portable data acquisition system to monitor the self-potential field over an area . The method has specialities: namely., to overcome the constraints of signal-to-noise ratio; minimizing the contact potential; fast data scanning - measuring each electrode potential in about 0.5 milliseconds with stacking up to 100 times and completing the scanning of 64 electrodes in about 32 milliseconds and displaying the image in fraction of a minute; averaging of the stacked data to improve the signal-to-noise ratio by a factor of 10 thereby reducing the external field influence and improving the precision of measurements. It has a facility for overcoming the natural variations in transient field and viewing the results of each measurement in the field itself immediately. This technology is unique in data acquisition and immediate display of SP image in the field itself, which helps in planning further exploration. To best of our knowledge, there is no equivalent technology elsewhere in the world. The application of the technology has been verified for ground water and mineral exploration. The imaging instrument with accessories and the output response for groundwater and mineral exploration are shown in Figure.9. This technological development in instrumentation is filed for patenting (CSIR Ref. No.0173NF2008).

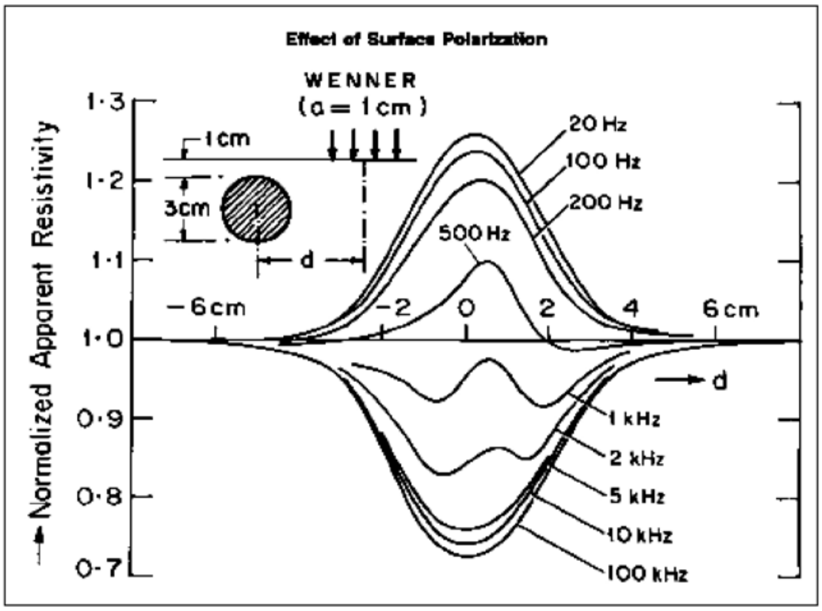


Figure 10. A metallic target immersed in an electrolytic medium behaves like an insulator low frequencies. Profiles of the magnitude of apparent resistivity normalizes by the resistivity of the medium were obtained with a 3cm diameter, 12 cm long horizontal aluminum cylinder at a depth of 7 cm from the surface using Wenner array with a=1cm along a profile across cylinder axis passing over the center of the cylinder. The medium was ordinary tap water. (After GuptasSarma,1983)

SPECTRAL INDUCED POLARISATION (SIP) STUDIES

Spectral IP studies on buried scale models incorporating surface and volume polarization is another significant contribution from NGRI. In resistivity modeling, the normalized apparent resistivity magnitude vs phase spectra are obtained over a metallic target, which is buried in tap water. If the excitation frequency is not high enough, polarization effects interfere at the interface between the target and the electrolyte. At lower frequencies the interface impedance is frequency dependent and does not obey scaling laws. Detailed study of the variation of frequency of maximum phase shift (Fm) with target dispositions with respect to an array and its size was discussed by Gupta Sarma and his group. Figure 10 shows the variation of frequency over a metallic cylinder (Gupta Sarma,1983) .

Spectral measurements of apparent resistivity and phase shift using a two electrode array or a Wenner electrode array over a cement-graphite sheet model immersed in an electrolyte (i.e. volume polarization), reveal that the frequency of maximum phase shift, Fm, varies with the array geometry and its disposition with respect to the target model. (Gupta Sarma1983, Apparao et al 1983). This suggests that practical mineral discrimination by measurement of spectral IP may only be a remote possibility. However, the Fm, for a given electrode array, is much smaller for a metallic model of the same dimensions, immersed in the same electrolyte. This means that in order to do accurate resistivity modeling, the excitation current frequency needed is much less than that is required in the case of the metallic model under the same conditions. The model tank apparent resistivity responses over the cement-graphite model sheet measured wit time domain IP equipment very much resemble the corresponding resistivity responses obtained over a metallic model of the same dimensions under similar conditions. Practicing geophysicists should keep this result in mind when interpreting IP field data. The mineral discrimination concept has been revisited by NGRI (Sarma et al 2006,2008) and it was observed that it could be possible to discriminate between the minerals, for example graphite and sulphide , using spectral induced polarization (SIP) studies.They have converted T-D to F-D and this theme has been addressed. (Figure.11)

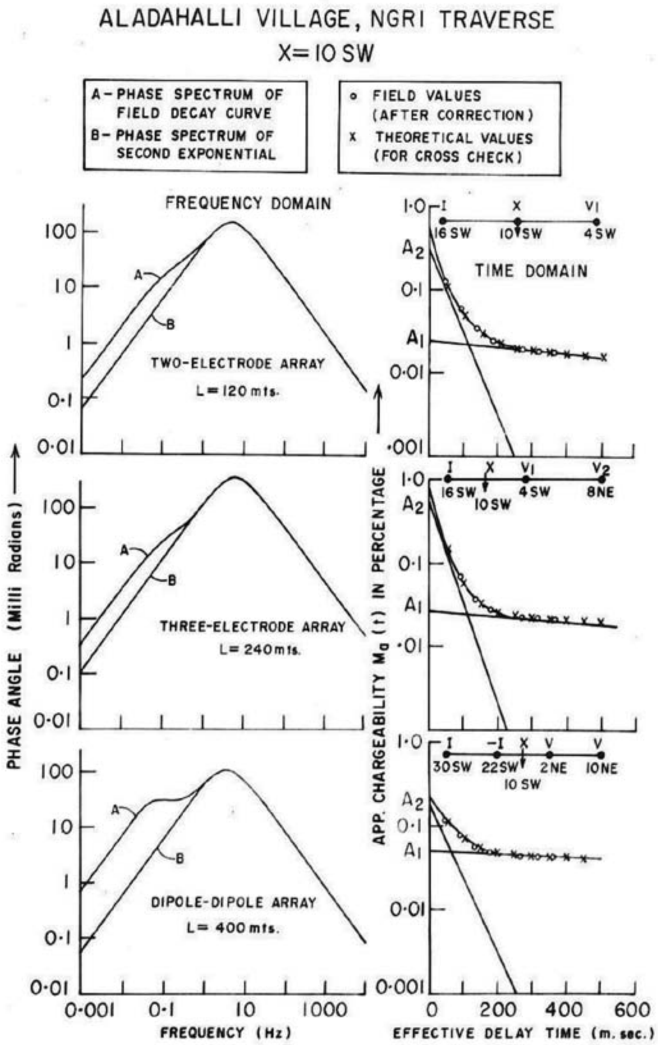


Figure 11. The right hand side represents the T-D decay curve and left hand side the corresponding phase spectra in F-D.with different arrays. (After Sarma et al 2006 and 2008)

ELECTRAL RESISTIVITY TOMOGRAPHY (ERT) STUDIES

Another significant contribution by NGRI is the application of Multi-electrodes for carrying out High resolution Electrical Resistivity Tomography (HERT) studies**.** The multi electrodes (Griffiths et al.1990; Barkar1992) with multi-core cables (Griffiths and Barkar1993) play a very significant role in the resistivity/IP prospecting, for detecting sub-surface formations and for studying geological strata architecture. In this type of surveys, a number of electrodes are planted on the ground surface maintaining an equal inter-electrode separation. The number of electrodes may be 12,24,48,72 or 96….. depending upon type of the measuring system. For the surveys by various groups in NGRI, imaging systems are used for the field and lab studies. Most of the conventional electrode arrays viz., two-electrode, three-electrode, Wenner; Dipole-Dipole etc have been applied in different geological environs.

These studies have been extensively carried out in different geological environs for understanding subsurface strata architecture with precision, high accuracy and reasonable resolution. Extensive applications are made in different corridors viz., the Ganga, Brahmaputra and Cauvery (Sarma et al 2006, 2007, 2008) for studying the shallow subsurface nature and the responses of the subsurface structures and formations. Tomography studies were carried out for pollution studies (Srinivasamoorthy et al 2009, 2010) and for sea water intrusion assessment (

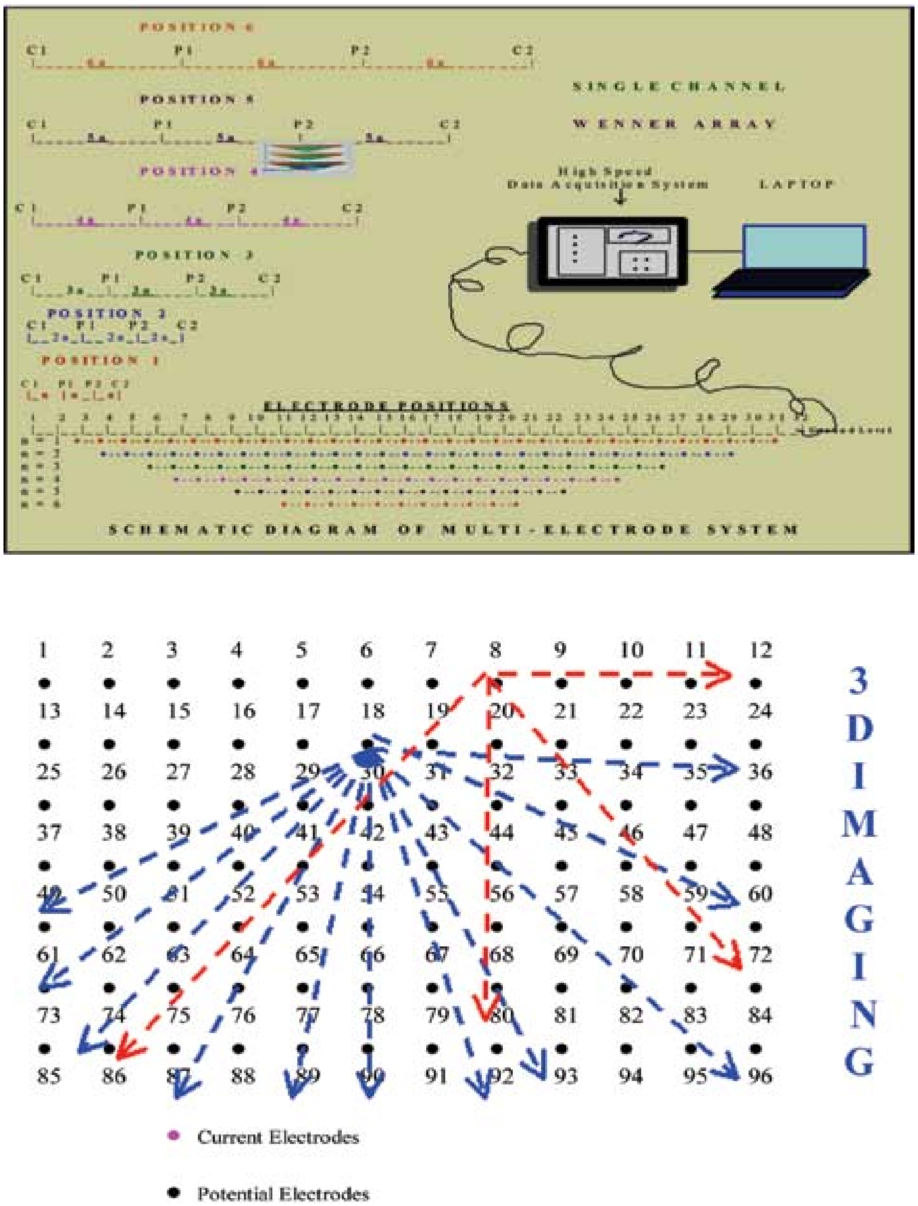


Figure 12. (a) 2D HERT electrode arrangement with depth levels.(top) (b) 3D HERT Field Arrangement (12*8 grid) (bottom) . (Source from Griffiths and Barkar, 1990 with modification)

Satish et al.,2011a, 2011b).As a significant approach Tomography studies have been applied in India by NGRI , using multi-electrodes for detection of industrial pollutants. Studies have been carried out in Tirpur of Tamilnadu to demarcate fresh water and sea water interface .Similar studies have been carried out also along a beach transect from Visakhapatnam to Bhimili (Sarma et al 2009). Figure 12 illustrates the scheme of the multi-electrodes in Electrical Resistivity Imaging for scanning of the sub-surface. In this, a series of profiling is carried out in a systematic way so that the subsurface is thoroughly scanned and consequently a subsurface image is obtained. RES.2D and RES. 3D software are applied for Inversion and finally a true resistivity 2D/3D subsurface structure is obtained. For getting an in-depth understanding of the geological formation at a specific depth, software, called 'slicer-dicer' is applied. Figure 13 represents 2D electrical resistivity image and 3D along with slicer image from the Cauvery corridor. In all the images, the locations for drilling the boreholes are recommended basing on the subsurface resistivity

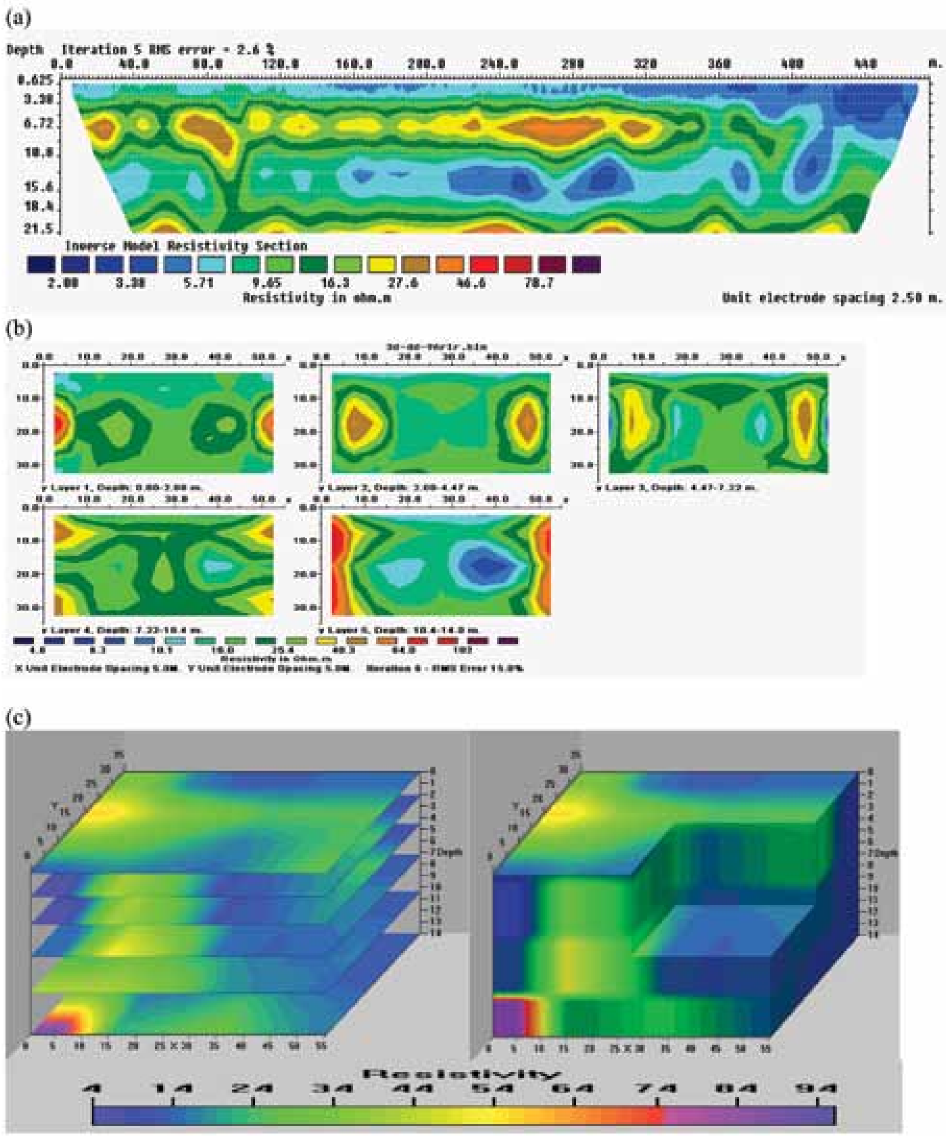


Figure 13. (a) 2D True Resistivity Cross section (b) 3D integrated cross section for different depth integrations (c)3D slicer images of Dipole-Dipole Configuration at Kadalangudi, Tamilnadu. (Sarma et al 2007)

distribution, local geology and geomorphologic significance. A good corroboration between the geoelectrical resistivity images and borehole lithologs and electrical logs has been achieved. This is illustrated in the Figure 14. Application of 3D geoelectrical resistivity for delineation of industrial dump has been carried out by V.S.Singh et al (2009). Cost-effective grid orientation for 3D data acquision has been put into practice by Aizebeokhai Philips A, A.I (2011) for groundwater exploration . The same authors have done extensive studies for finding out relative advantages of 3D over 2D in delineation of hard rock shallow aquifers(2010).

Other researchers from NGRI also carried out extensive studies. Kumar et al (2010) besides finding out the advantages of ERT over the conventional arrays interpreted 2D inverted resistivity models of the subsurface that represent the hydrogeological conditions, structural features, resistive and conductive formations (Kumar, 2004; Kumar et al., 2007; Kumar, 2012). The method is found to be well suited for characterization of crystalline basement rocks and their weathered regolith profiles (Kumar et al., 2011). Interpretation of computed resistivity models along eight profiles at 4 hot spring sites indicates the presence of potential geothermal reservoir (Kumar et al., 2011). Hydrogeological and geophysical study for deeper groundwater resource in

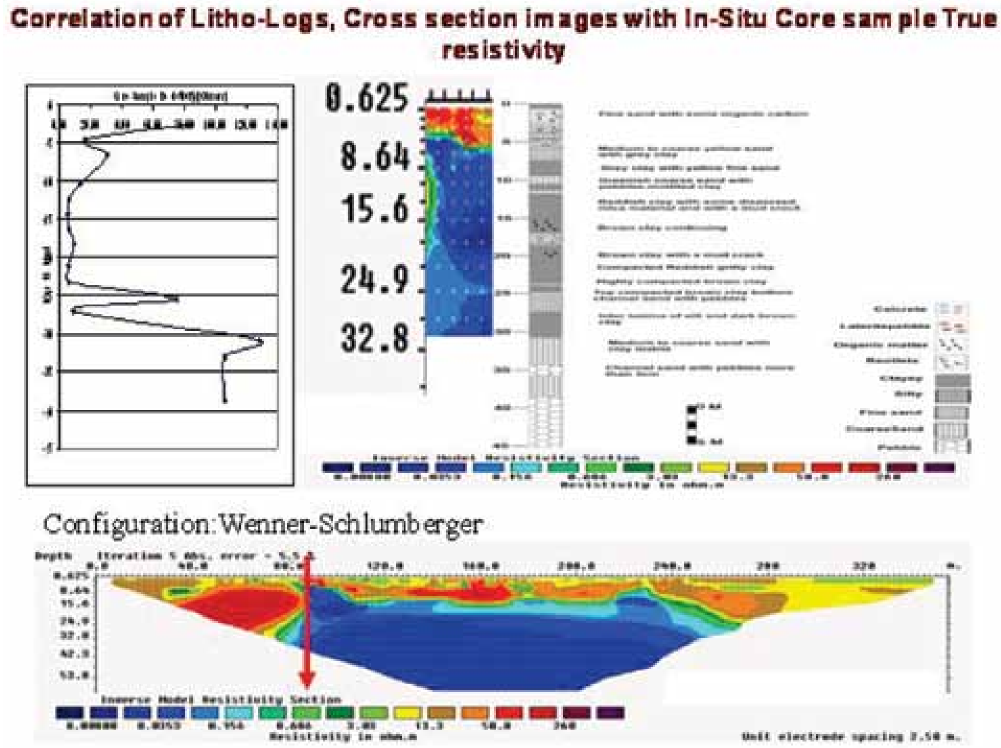


Figure 14. Correlation of lithologs,1D,2D images in Cauvery corridor. (Sarma 2009)

quartzitic hard rock ridge region from 2D resistivity data has been studied by Kumar et al.,(2013). Another group(Rai et al,2011a) also carried out such studies in this theme in the Deccan traps occupied by Chandrabhara river basin in Nagpur district. The basin is facing acute shortage of water supply for irrigation and domestic usages.

Excellent application of the imaging technique is that it has proved to be a powerful tool in the study of the types of concealed lineaments (Mondal et al 2008) as well as groundwater exploration. Hydrogeophysical characterization of unsaturated zone, using geophysical and geostatistical tools is deeply studied (Arora,2008). She invented a new methodology for estimating the variograms which is especially favourable for sparse datasets in hydro-geophysics. This is the first doctoral research work in India (NGRI) over unsaturated zone. The same group (Arora and Ahmed, 2010 and 2011) have captured the spatio-temporal variability of unsaturated zone through geophysical inputs and application of geostatistical tools. In her book (Arora,2013),she has demonstrated the importance of vadose zone studies and carried out Time Lapse Electrical Resistivity Tomography [TLERT] experiment to find out the relationship between electrical resistivity of unsaturated zone and soil moisture measurements. Using the HERT, excellent contribution is made in coal bearing zones of Singareni Colleries and also in Kimberlite formations near Anumpalli area of Andhra Pradesh (Verma et al 2005 and 2006).

Deccan traps occupied Chandrabhaga river basin in Nagpur district is a part of draught prone Vidarbha region ,which is infamous for farmer's suicide. The basin is spread over in 500 Km^2 and encompassing 50villages of Katol, Kalmeshwar and Rural Nagpur taluks. The basin is facing acute shortage of water supply for irrigation and domestic usages. Vertical electrical Sounding at 45 sites and Electrical Resistivity Tomography at 56 sites have been carried out for delineation of groundwater potential zones and suitable sites for managing aquifer recharge. Based on this study groundwater potential zones have been delineated in weathered mantle above the traps, intertrappeans and fracture zones within the traps and Gondwana sedimentary formation below the traps at more than 70 locations (Rai et al., 2011a, 2012a, 2012b, 2013a; Ratnakumari et al, 2012). Presence of groundwater potential zones has been verified by bore well drilling at 7 locations. An example of yield of a bore well drilled at a VES site under Raulgaon village is shown in Figure 1. Based on this study it is concluded that the present scarcity of water supply in Vidarbha region can be overcome by delineation of groundwater potential zones followed by their development using recently developed Electrical Resistivity Tomography techniques and by managing aquifer recharging at identified locations.

Similar studies for the delineation of groundwater potential zones and suitable sites for managing aquifer recharge using Electrical Resisitivity Tomography have been carried out in Deccan traps occupied Chiplun taluk of Ratnagiri district (Rai et al, 2010, Kumar et al, 2011), Tadkeshwar Lignite Mine area in Surat district (Rai et al , 2011b), Granitic terrains of CSIR- National Geophysical Research Institute campus (Rai et al 2013b), CSIR- Centre for Cellular and Microbiology (Rai et al 2013c) and in the campus of CSIR- Indian Institute of Chemical Technology (Rai et al 2013d). In the usual way NGRI has been addressing scientific problems which bear a societal benefit. In this way many problems of ground water occurrences have been sorted out in Cuddapah basin area. Another such problem was solved in Deccan traps as illustrated in the Figure.12.

Other significant Initiatives

NGRI has been carrying out conventional resistivity surveys since late sixties in many parts of the country and in particular, in Cuddapah basin area (Balakrishna and group) for finding out groundwater zones for local residents, as a part of societal relevance. In a significant way ,the field surveys to identify potential ground water sources was initiated under the stewardship of S.Balakrishna. Further, using the experiences gained over 15 years K.R.Ramanuja Chari and M.Pandurangam , on taking voluntary retirement established their own instrument manufacturing units and resistivity survey wings.They basically used acquired knowledge from NGRI and patent of NGRI. They significantly propagated the importance of resistivity technique in locating potential ground water sources, in different parts of the country.

Making using of personal interaction with theoretical and field scientists of NGRI, P.R.Reddy as Scientific Advisor of A.P. State Irrigation Development Corpn (On deputation for ~3 YEARS-1983 TO 1985) has significantly propagated the importance of resistivity technique in locating potential ground water sources in drought hit segments of Andhra

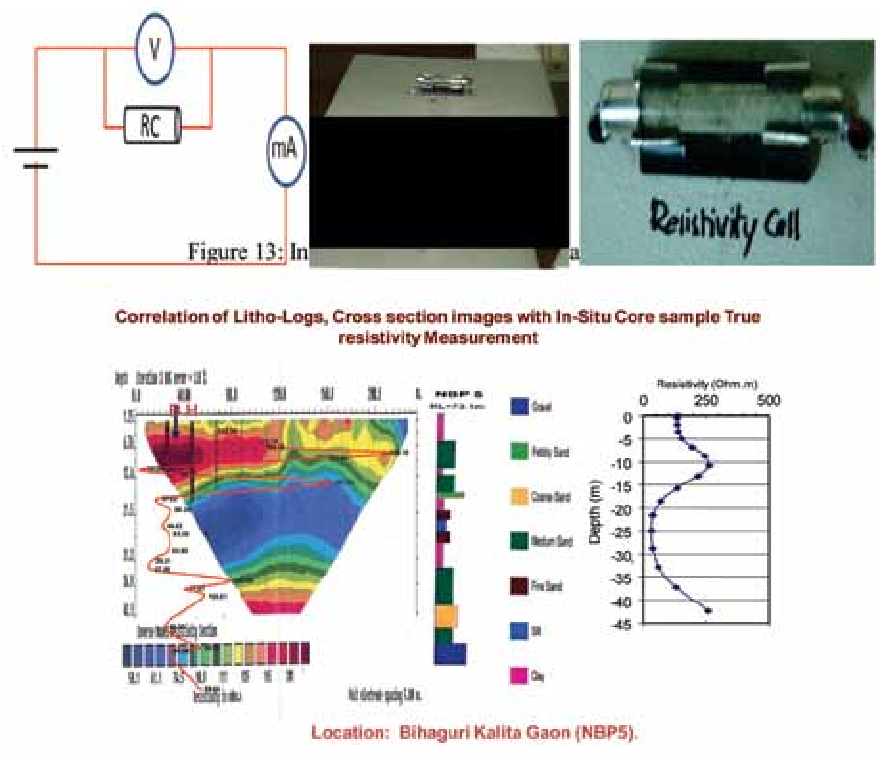
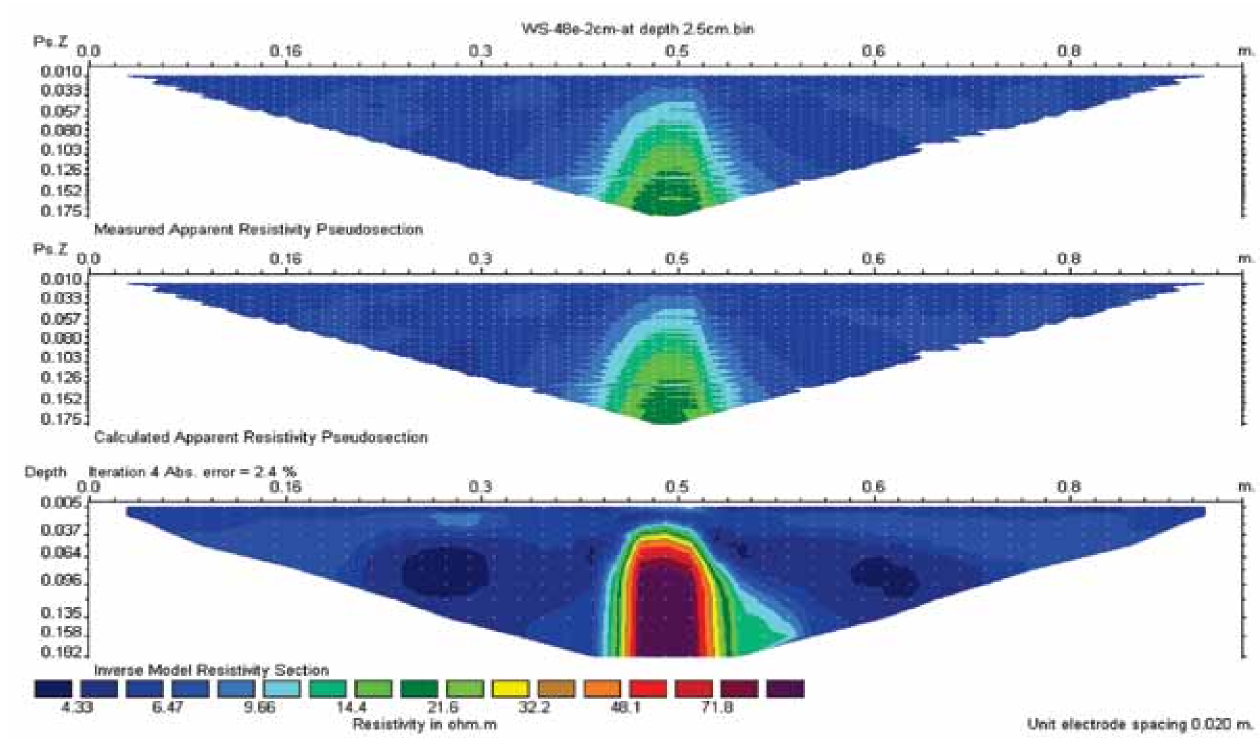


Figure 15. Response characteristics obtained with core sample sensor and calibrated with 2D and 1D section. (Sarma and Rajesh ,2011)

Figure 16. Multi electrode setup for Physical Model Experiments using Automatic Resistivity meters (Sarma and Rajesh 2011)



Target depth from water surface: 3 cm

Figure 17. Wenner-Schlumberger 2D cross section over vertical granite sheet of thickness 1cm using 48 electrodes with 2cm inter electrode spacing. (Rajesh et al 2013)

Pradesh. He, taking the assistance of dedicated hydrogeologists and geophysicists located more than 4000 potential zones using Linear Resistivity Profiling, VES and Radial Profiling. In total more than 30,000 acres were brought under irrigation using more about 3000 borewells drilled during that period. Conjunctive utilization of surface and sub surface waters has been introduced to optimally use the available water. Also an Atlas was brought out depicting relative ground water potential of different segments of A.P. As a case study his team has also brought out vertical and lateral extension of weathered mantle , fractured column and gneissic basement topography of two taluks of Chittoor dist, which subsequently helped in taking up revitalization exercises by APWELL and APFMAG projects .

Under National Drinking water technology Mission significant studies have been carried out by NGRI scientists (A.Apparao and V.S.Sarma 1982-89) to provide drinking water to many segments of the country, including parts of Rajasthan,U.P, W.Bengal, Karnataka, A.P, Tamilnadu and NE India.

LABORATORY STUDIES

Figure 15 illustrates a measuring instrument designed and fabricated by NGRI (Sarma and Rajesh, 2010) for finding out the true resistivity of the core samples at the core sample room temperature. This is one way of confirming the true resistivity of the core sample with the subsurface resistivity where a good calibration is achieved.

NGRI has pioneered in carrying out the Physical model studies with an objective that 'an appriori' knowledge of the field targets could be obtained so that field survey could be planned. Using the SYSCALPro-96 measuring system ,which has been extensively used in the field studies, scale model studies have been carried over natural samples to understand their in-situ nature. Parametric studies have been carried out using multi-electrodes. Figure 16 illustrates the schematic diagram of the model tank with multi-electrodes as designed by NGRI (Sarma and Rajesh,2010, Rajesh et al, 2013). Figure 17 shows a simulated geological situation with a sequence of natural material with the corresponding true resistivity image. For measuring the responses of the in-situ samples, a 3D measuring device is developed in the physical model lab (Sarma and Rajesh,2011).

CONCLUSION

To propagate importance of any scientific study, it is essential to bring in to focus chronological development of a technique or a study. NGRI as an internationally recognized research institute has contributed significantly in developing Electrical resistivity technique. Many a time , due to lack of exposure to recent scientific and technological developments grass root level scientists and technical assistants are forced to face many area specific problems in selecting proper recording geometry and interpreting the acquired data. To partly address this problem this write up has been prepared, knowing very well the information covers only a limited part of the significant strides made by NGRI scientists. I do,however, believe the information would be useful to the scientific community in general and young researchers and students in particular.

ACKNOWLEDGEMENTS

The author is grateful to Prof.Mrinal K.Sen, Director, CSIR-NGRI for constant encouragement,to contributors for furnishing their respective study particulars on my request,at a short notice .I am thankful to Prof.P.R.Reddy, NGRI for suggesting this theme and for very useful suggestions in refinement of the paper. I am also grateful to Prof.Reddy for meticulous editing of the manuscript. But for his guidance and help this paper would not have seen light of the day.

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