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The Development of a New Rhombic Array in Electrical Resistivity Prospecting

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Abstract

A new array of four electrodes, placed at the corners of a Rhomb or Diamond shape consisting of two equilateral triangles, having equal sides with a short diagonal of the same length as the side and a long diagonal with length equal to (√3) times the side length has been developed and described. This array exhibits different layout shapes according to the position of the short diagonal (a) with respect to the traverse line, which is normal to the strike of the body. As no previous study of this new system had been carried out, tank analogue experiments over high resistivity, concealed model was considered, and a field test was carried out to prove its usefulness. The objective of this model experiment is to study, examine and assess the behavior, response and sensitivity of different orientation Rhombic systems over such model, in order to establish the best layout, which can be used for further experiment studies and fieldwork investigation. However, and by comparison the new system with the most conventional one (Wenner array), the results obtained in the field tests by the Rhombic array have its higher performance and superiority over the Wenner with regards to anomaly shape, magnitude and position when a vertical body was conducted, (i. e the signal is quite improved).

Key wards: Geophysics; Electric; Development; New Rhombic Array.

1. Introduction

Many layouts of electrodes in earth resistivity measurements have been proposed and studied theoretically and experimentally since the Wenner and Schlumberger arrays demonstrated the usefulness of such measurements over ninety years ago.

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The main objectives of these proposed arrays are to simplify the resistivity calculation, to facilitate the layout in the field, to increase sensitivity to the geological signals, to reduce or eliminate extraneous factors and to increase the speed of operation. It is convenient to classify the layouts into three main groups. The first group, namely the linear arrays with four electrodes in a straight line was the earliest to be used and still account for most of the applications because of the relative simplicity of setting out the electrodes in the field and the ease of calculating the resistivity from the resistances measured. The Wenner and Schlumberger arrays are two of the earliest, simplest and most widely used of this linear group, along with three electrode arrays such as half Wenner and half Schlumberger, crossed equi-spaced three electrode array and the modified Schlumberger, [25, 21, 12, 17, 6, 20, 10, 16, 2 , 3].

Collinear arrays similar to the Wenner arrangement have also been proposed with variations either in the potential spacing, i. e the ratio of potential electrode separation to the current electrode separation, (t/L) [4], or in the number of electrodes in the Lee-position layout of five electrodes in which the third potential electrode is located at the center (P) of the spread, i. e C1P1PP2C2 [22]. A further layout of seven electrodes as A1M1M1' A M2M2'A2, called surface latero-log, devised for well logging, has been applied as a surface equivalent suitable for geophysical exploration [5].

The two electrode system can also be regarded as a special form of Wenner array and is extremely rapid because only two electrodes (C1P1) have to be moved usually with a fixed spacing automatically measured out by connecting cable with the outer two located at a long distance from the survey electrodes [17, 6, 7, 15, 18 & 23].

The second group namely the non-linear arrays with four electrodes, generally are not spread in a straight line. The Dipole-Dipole array, suggested by [8] with a description and comprehensive interpretation in [17] is one of this group. Such an arrangement includes two pairs of electrodes whose spacing are constant, the current electrodes being usually fixed, and the potential electrodes being moved across the search area in various regular patterns.

Depending on the attitude of the measuring potential dipoles with respect to the current dipoles, six different arrangements can be set out in the field. The first arrangement, called axial, can be considered as linear and the other five arrangements are set out non-linearly and are called parallel, perpendicular, radial, azimuthal and equatorial. These arrangements simplify the fieldwork but cause complications in the resistivity calculations. The principle advantage of the Dipole-Dipole arrays is that the pattern of potential electrodes can be related to various geophysical circumstances in the field and can be used for deep electrical sounding investigations. Against these advantages, the geometric factor expressions for these various arrangements are fairly complex, but their magnitudes are large and increase very rapidly as the distance between the two Dipole centers is increased which then the result in a requirement for move electric instruments with high sensitivity. The Bipole-Bipole, introduced by [26], in which the same principles and variety of arrangements was used, except that the distance between the centers of the Biploe and the Dipole is not larger than half the current electrode spacing overcomes these prohibitive requirements. However, although the geometric factor is smaller in magnitude, a complexity in form results. The Bipole-Quadripole [9], and Quadripole-Quadripole [11], are further techniques that have been suggested and belong to the present group. Both techniques are used to provide apparent resistivity, which are measurements orientationally independent, and the last array has shown its ability to yield more meaningful information than the former but with a higher labor requirement.

The third group of layouts can be desired as two dimensional, being turned effectively into three-dimensional methods by variations in spacing. The Square array introduced by [13], some fourty-five years ago, was found particularly useful in case where the orientation of the geological discontinuity was not known. This meant that the linear array could not be oriented perpendicular to the discontinuity and consequently the anomalies produced from the linear arrays were diffuse and sometimes not detectable. The Square array could also be used to identify lateral or directional variations in resistivity by the application of the "Tri-potential rule" which is used in linear array as a field – check since ($R\alpha = R\beta + R\gamma$). The variations in resistance are measured in only one direction, along the array line.

In the two dimensional arrays, the Tri-potential rule relates to resistance measured in different directions and in homogeneous ground ($R\gamma$) should be zero and ($R\alpha = R\beta$) . Deviations of ($R\gamma$) from zero indicate the non-homogeneous nature of the ground tested.

The Square array, however, does not to be closely controlled. The placing of electrodes in a Square requiring more skill than the placing of linear arrays and also it is not sensitive in respect of the perpendicularity of profiles relative to the discontinuity. Hence, it was proposed to device a Rhombic array, consisting of two equilateral triangles, the Rhomb thus having equal sides with a short diagonal of the same length as the sides and along diagonal with length equal to ($\sqrt{3}$) times the side length.

As demonstrated above, many arrays and configurations have been proposed, established and used in the electrical resistivity studies. Each one of these arrays may have a special circumstance in which it will be used, according to its advantages and limitations. The selection of a particular electrode array is controlled by many variables with the most important one being the strength of the anomalous response of the array over a given type of target, which is being sought. The purpose of the project, the power and the sensitivity of the equipment, the time and speed that is needed to achieve the field work, the man-power needs, the general view of the area under investigation, the back ground noise level, the ease of the resistivity calculation and the ease of interpretation of the collected resistivity data, are the other considerations that should be taken into account when an array has to be chosen.

However, the Rhombic array was tested in a large brine tank to verify its theoretical basis, which then a test against the conventional Wenner array in the field was made. The main objective of the present work is to develop the tank experiment and then to study, examine and assess the behavior, response and sensitivity of different orientation Rhombic systems over the dyke model, in order to establish the best lay out which can be used for further experiment studies and fieldwork investigation.

2. The development of the Rhombic array

The Rhombic array has been developed as an alternative to Square array which consists of four electrodes arranged in the form of two equilateral triangles with a common side as in (Fig 1a, b, c and d). C1, C2 are current electrodes and P1, P2 are potential electrodes across which resistance is measured. It will be noted that all sides and the short diagonal have equal length as (a) whilst the remaining long diagonal has a length of (√3) times the side length.

Measurements when P1P2 runs NE-SW in the diagram are referred to as (α-configuration), Fig 1a, whilst measurements with P1P2 along the other two sides of parallelogram are referred to as (β-configuration), Fig 1b, and measurements with P1P2 as diagonals are designated (γ1 & γ2 configurations), Fig 1c & 1d.

The original idea behind the Rhombic array was that equilateral triangles are easier to set out in the field compared to the Square. In fact the Rhombic array has proved to have another advantages compared to the Square array and to other arrays such as Wenner, three-electrode particularly with regard to sensitivity.

In this context, the investigation and assessment of the behavior, response and sensitivity of different orientation Rhombic system over dyke model to establish its best layout which can be used for more experiments and field investigations was carried out.

3. Theoretical Consideration

There are twenty-four possible arrangements of electrodes (C1, P1, p2 & C2) since C1 & C2 can be regarded as interchangeable with P1 & P2, Table 1. It was found that only rarely do the resistances of opposite sides of the parallelogram differ appreciably, Table 2, so that in most subsequent tests only four measurements were made corresponding to two adjacent sides of the Rhomb and two diagonals. This enables resistivities to be determined in four directions, three forming an equilateral triangle and the fourth bisecting the angle between two of these three. In this circumstance, the orientation of profiles relatives to the anticipated anomalous feature is not so critical with the use of this multi-directional approach. Hence, the array has advantage where little is known about the geological structure of the study area.

Supposing that a current (I) introduced from the point source or sink is passing through a uniform semi-infinite homogeneous and isotropic resistivity medium, the potential at a point due to the electric point source can be given by applying the (equation 1) below:

$$\Delta V = V_{p1} - V_{p2} = [I\rho/2\pi][(1/C1P1)-(1/C1P2)-(1/C2P1)+(1/C2P2)] \ldots\ldots\ldots (1)$$

Then the electrical resistivity of the Rhombic array can be determined. (Fig 1a), shows (α-configuration):

$$\Delta V=[I\rho/2\pi][(1/a)-(1/a)-(1/a\sqrt{3})+(1/a)]$$

$$\Delta V=[I\rho/2\pi][(\sqrt{3}-1)/a\sqrt{3}]$$

$$P\alpha = [2\pi a / 1-(1/\sqrt{3})] * R\alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

This equation can be simplified to be in the form as:

$$\rho\alpha = [2\,\pi a\, R\alpha / 0.42265] \text{ ……………………………}(3)$$

$$\text{Or } \rho\alpha = 14.866\, a\, R\alpha \text{ ………………………………..}(4)$$

In the same manner and according to (Figure 1b):

Table 1: 24 possible configurations of the rhombic array (Arrangements 1,9,17 and 21 appear in Figure 1)

	W	N	E	S		W	N	E	S		W	N	E	S		W	N	E	S
1	C1	P1	P2	C2	5	C1	P2	P1	C2	9	C1	C2	P2	P1	13	C1	C2	P1	P2
2	C2	P1	P2	C1	6	C2	P2	P1	C1	10	C2	C1	P2	P1	14	C2	C1	P1	P2
3	P1	C1	C2	P2	7	P2	C1	C2	P1	11	P2	P1	C1	C2	15	P1	P2	C1	C2
4	P1	C2	C1	P2	8	P2	C2	C1	P1	12	P2	P1	C2	C1	16	P1	P2	C2	C1
α – configurations										β – configurations									
17	C1	P2	C2	P1	19	C1	P1	C2	P2	21	P2	C2	P1	C1	23	P1	C2	P2	C1
18	C2	P2	C1	P1	20	C2	P1	C1	P2	22	P2	C1	P1	C2	24	P2	C1	P1	C2
γ_1 – configurations										γ_2 – configurations									

Table 2: shows the field resistance measurements of rhombic 24-arrangement and four configurations, at fixed point, spacing=3 meters

Configuration	Electrode Arrangement				Resistance (ohm)	Av. Resistivity (ohm.m)
α1	C1 C2 P1 P1	P1 P1 C1 C2	P2 P2 C2 C1	C2 C1 P2 P2	1.655 – 1.653 1.655 – 1.655	73.788
β1	C1 C2 P2 P2	C2 C1 P1 P1	P2 P2 C1 C2	P1 P1 C2 C1	1.826 – 1.826 1.828 – 1.827	81.470
α2	C1 C2 P2 P2	P2 P2 C1 C2	P1 P1 C2 C1	C2 C1 P1 C1	1.655 – 1.656 1.653 – 1.654	73.788
β2	C1 C2 P1 P1	C2 C1 P2 P2	P1 P1 C1 C2	P2 P2 C2 C1	1.825 – 1.825 1.828 – 1.828	81.460
γ1	C1 C2 C1 C2	P1 P2 P1 P1	C2 C1 C2 C1	P1 P1 P2 P2	0.175 – 0.173 0.173 – 0.173	
γ2	P2 P2 P1 P1	C2 C1 C2 C1	P1 P1 P2 P1	C1 C2 C1 C2	0.175 0.175 – 0.175 0.173	

α1 = α2 = α

β1 = β2 = β

$$\rho\beta = 14.866\ a\ R\beta \quad \ldots\ldots(5)$$

Then, theoretically $(R\alpha/ R\beta) = (P\alpha/ P\beta) = 1$

(Fig 1c), shows the ($\gamma 1$ configuration) in which P1 & P2 lies along the diagonal of length ($a\sqrt{3}$).

$\rho\gamma 1 = 0$, since $G\gamma 1=[(1/a)-(1/a)-(1/a)+(1/a)] = 0$. Thus, ($\rho\gamma 1$) can be not calculated. Similarly in (Fig 1d) the ($\gamma 2$ configuration), in which P1 & P2 lies on the short diagonal of length (a), since $G\gamma 2 = 0$ and then $\rho\gamma 2 = 0$, so that ($\rho\gamma 2$) can be not calculated either.

However, the most natural circumstances, it is possible to measure ($R\gamma 1$ & $R\gamma 2$) and the Tri-potential rule, ($R\alpha = R\beta + R\gamma$), will still apply. Only in homogeneous, isotropic medium will be found that ($R\gamma 1 - R\gamma 2=0$) and ($R\alpha = R\beta$).

Hence, the difference between measured values (($R\alpha$ & $R\beta$) can be used as a measure of lateral variation of the subsurface rocks whilst their main value is less dependent on the orientation. This was pointed out by [13] with respect to the Square array.

Consequently, since the Rhombic array has shown a similarity to the Square array in its principle, the definition of the azimuthally in-homogeneity ratio (A.I.R) can be used as well.

4. Resistivity Investigation and Rhombic Array Tests

Although a mathematical model can be considered as a rapid tool using computer programs and can offer a wide range of various parameters used, some limitations were commonly displayed due to length, complexity and difficulty of the process. Further, some deficiencies were revealed in the parameter coverage such as the effect of the body depth which is an important factor affecting the resistivity measurements from the earth's surface.

Because of the complexity of the mathematics involved in the theory of such models, an alternative technique has been considered. This technique used a plastic tank analogue filled with brine solution as proposed by [24]. Since then frequent use of such a tank been made using different materials to simulate resistivity models [5]. The tank experiment comprises of three components namely, brine solution, concrete slab model and electrode arrays used to study their response and behavior.

5. Brine Solution and Concrete Resistivity Investigation

Many sets of brine solution resistivity values of the same concentration were determined by using the Whetstone Bridge with two calibrated cells.

One of these values was selected as (100 ohm.cm), in which (Fig 2) shows the profile of resistivity measurements of the brine solution by Rhombic array in the tank without any slabs immersed in it. This figure clearly illustrates the absence of any wall effect along a traverse line of (150 cm) length taken in the middle of the tank. On the other hand, different materials were tried to simulate an anomalous resistivity body by many geophysicist for example, Perspex, aluminum - copper sheet and ebonite.

Eventually [5] found the mixtures of graphite and cement gave usable results [14], conducted a few tests of ternary systems of mixture composition which contained sand, cement, graphite even [19] made a further investigation in which core sample of different compositions were measured.

In order to cover a range of model resistivity contrast which were also strong enough to resist corrosion due to brine solution and to get more information about these compositions behaviors which could be added to earliest work, the same ingredients as sand, cement and graphite were used and found to be most suitable materials for the present model experiments. However, some derived values belongs these samples (i. e formation factor and resistivity contrasts) were revealed in (Figure 3, 4, 5 and 6) respectively.

In general, the use of these constituents in different ratios has proved its usefulness in covering a wide range of resistivity contrast.

Well, the block model dimension were (100 cm) long, (50 cm) depth extent and (5 cm) wide with a composition of (60% cement, 15% graphite and 25% sand), this mixture should yield a poorly conducting block as a dyke-like target with an average resistivity of (710 ohm.cm), which shows an order of contrast (7.1/1.0), the resistivity of brine solution taken is (100 ohm.cm).

6. Arrangement of the Experiment

a- Model Used and System positioning

The block model (dyke) with a width of (5 cm) was suspended vertically (dip=90) in the middle of the tank at a depth of (0.5 cm) below the brine surface, the strike of the dyke being perpendicular to the traverse line, which is in a direction parallel to the length of the tank. These parameters were fixed for all tests in this experiment, while the spacing and Rhombic system orientation was varied.

The spacing taken was (5, 10 & 20 cm) respectively for each profile orientation. The Rhombic system, on the other hand, exhibits five common layouts depending on the position of the short diagonal (a) with respect to the (north-south) traverse line which are represented as, either a(sd), (sd = short diagonal) along a traverse line (90° to the strike), a(sd) at N30°E to the traverse line 60° to the strike, a(sd) at N60°E to the traverse line (30° to the strike), a(sd) at N60°W to the traverse line (30° to the strike) or a(sd) at 90° to the traverse line (0° with the strike of the body).

b- Experiment Observation

To start with, the traverse line was selected in the middle of the tank, being perpendicular to the strike of the dyke with a maximum length of (100 cm), (50 cm) on either side of it. The station interval used was (5 cm), while this distance reduced to (2.5 cm) when the system was near the body (20 cm from the center position on each side). The system was set at an approximate orientation starting with a(sd) along the traverse line. All resistance measurements were taken by using ABEM Terrameter SAS 300B. The observational errors of the measured resistance were always within (± 3%).

7. Results and Analysis

A computer program was written for calculating the corrected Tri-potential resistances in order to yield corrected resistivities. These results were plotted as graphs showing the variation of the mean apparent resistivity with respect to the distance (x) for different spacing and orientation systems to reveal the nature, behavior and sensitivity of each orientation.

Consequently, by making a comparison between them a final conclusion could be reached according to the diagnostic characteristic features. The set of graphs (Fig 7, 8 & 9) illustrates the variations of the mean resistivity ratio ($\rho m/\rho 1$) against the distance (x), (x) being negative in the south side and positive in the north side, while its value was (0) at the center of the dyke.

From a comparison, these set of graphs revealed some important points which are discussed below:

1- All figures for different spacing and orientation have shown a clear anomaly positioned at the center above the dyke.

2- In general, the width of the anomaly increased as (a/w) was increased. On the other hand, the width decreased as the orientation was changed, (Fig 8 & 9), whilst (Fig 8) shows clearly two differentiated curves which are of great coincidence, (Fig 9) shows a gradual decreasing width. However, the width was increased slightly as the orientation was varied when (a=5 cm), (Fig 7).

3- From all graph sets, it can be seen that the magnitudes of the anomaly decreased with increased (a/w). On the other hand, the single set of curves for each spacing has shown that the magnitudes decreased with the orientation variations. However, a maximum magnitude is the diagnostic feature of the a(sd) along the traverse line.

4- It is clearly shown that the shape of the curves remains simple, constant and stable with a great similarity for all orientation curves when (a=5 cm) even the same for a(sd) along and at (30°NE) to the traverse line when (a/w) increased, whilst for other orientation curves, there can be seen a slight changes with some complexity in the shape of the curves, which can be described as a single high anomaly flanked by two sharp troughs with two small ridges beyond these.

8. Some Field Tests and Conclusions

It has been seen that the initial results allowed a qualitative analysis and comparison of the different orientation systems with respect to the traverse line. Hence, an assessment can be made through it, in order to find the best one to be adopted.

Thus, the conclusions arrived at from this analysis were then strengthen by conducting traverses in further experiments and by carrying out field work for different geological investigation. Graphs are displayed, showing the significance of orientation with respect to the known strike direction, so, an attempt was made to classify the obtained results to reach the main objective. However, in order to classify the anomaly results, it is considered that the ideal orientation should give an anomaly with large magnitude (i. e high sensitivity and response) and a simple shape (i. e behavior). A further factor taken into account in this assessment was the ease of reproducing the layout and the simplicity of carrying out investigations. From all the orientation system models, the a(sd) along the traverse line exhibits a maximum amplitude and a simple shape profile, hence its preference and superiority. To satisfy the third requirement, a field test to locate an artificial buried channel at the Horsforth (England) site was performed using different orientations. It showed that the above orientation had the simplest layout and was easy to carry out in comparison to the others. It also gave the same amplitude and shape results, (Fig 10). The Rhombic array gives an excellent anomaly response, but it shows an effect in its behavior relative to the orientation, similar to these revealed in the experiment profiles. Although, this complexity is apparent in the shape of the curves compared to the others, at least when a vertical dyke is encountered, the distance between the troughs can be used to advantage in estimating the width of the dyke model, this distance being apparently equal to (0.5 a) plus the width of the dyke model when (a = 10cm), whilst it seems to be equal to (0.75 a) plus the width of the model when (a = 20 cm). This estimating rule can be used as a guide to field data but must be treated with caution since the shape of the anomaly pattern is governed by the station interval. However, it was found that s(sd) along the traverse line provided the best results, therefore, this layout was adopted for further intensive experiments and field investigations. Well, another test was made at a natural structure represented by an igneous dyke body at Whiby site (England). A traverse line was conducted in terms of Rhombic – a(sd) along the traverse line and Wenner arrays with different spacing to collect data for the identification, comparison and correlation of resistivity features. The horizontal apparent resistivity profiles for both arrays are shown in (Fig 11 & 12) respectively. By inspecting those figures, it can be seen that, although all profiles for both arrays revealed a single high anomaly which represents the electrical nature of the dyke in respect to the surrounding rocks, the anomalies obtained by the Rhombic array are more pronounced and sharper. In addition, the sharp peaks of all anomalies are always positioned accurately at the probable location of the dyke center, which is (80 m) from the starting point. The simplicity smooth shape and the higher magnitudes are the most noticeable characteristic features of the Rhombic profiles as was confirmed by the laboratory results. These characteristics are not apparent in the Wenner profiles where the anomalies show less definition and some complexity of the profiles, with a single high anomaly flanked by two minor troughs with two small high beyond, except for the profile when (a = 5 cm) where the peak is flanked by two broad lows. It should be noticed that the speed of operation of the Rhombic array in the field along a traverse line is seen approximately as the same as the Wenner, even its layout is also seen to be easy to perform, further it does not required as many staff to achieve such electrical measurements in the field. In contrast to the advantages, the only limitation produced by the application of such an array is the setting up of the long diagonal ($a\sqrt{3}$) for which open space is needed. However, this limitation can be reduced. This long diagonal can be represented by a strong cord, knotted and labeled for various spacing. However, was anchored at its center by a double tee pin as shown in Fig (13), locating always at the measuring station. Such a cross has a great advantage in that the long diagonal can be set out precisely at right angles to the short one, since one of these tee shapes was along the short diagonal.

Finally, the tank analogue experiment showed its usefulness and effectiveness in resistivity model studies, for establishing this new system. In addition, it provided a precise enough test to test the Rhombic array in comparison with the other systems in the future.

9. Recommendations

Although the tank model utilized in the present study has revealed its effectiveness as an important tool to display the general behavior and response of the Rhombic array, a comprehensive and detail study for different simple geological situations as (dyke, vein, fault, horizontal layers..etc) has been achieved, however, further work should be carried out to study the physical characteristics of this array in the presence of more complex models which stimulate more complex geological environments such as the presence of anisotropy, multiple conductor or insulator bodies and so on, in fact, such investigation could be achieved by using theoretical models.

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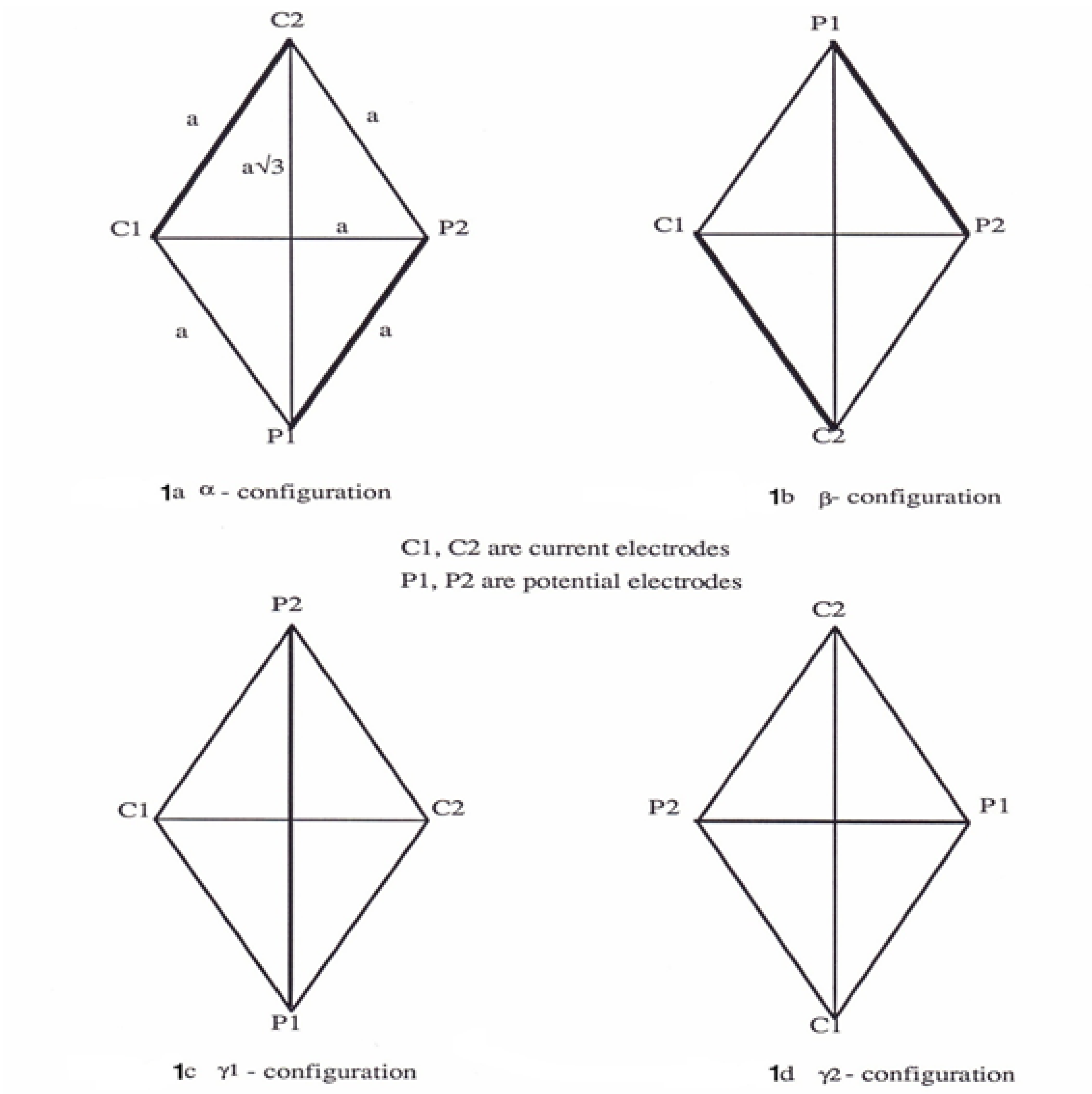

Figure 1: Different configurations of Rhombic lay out

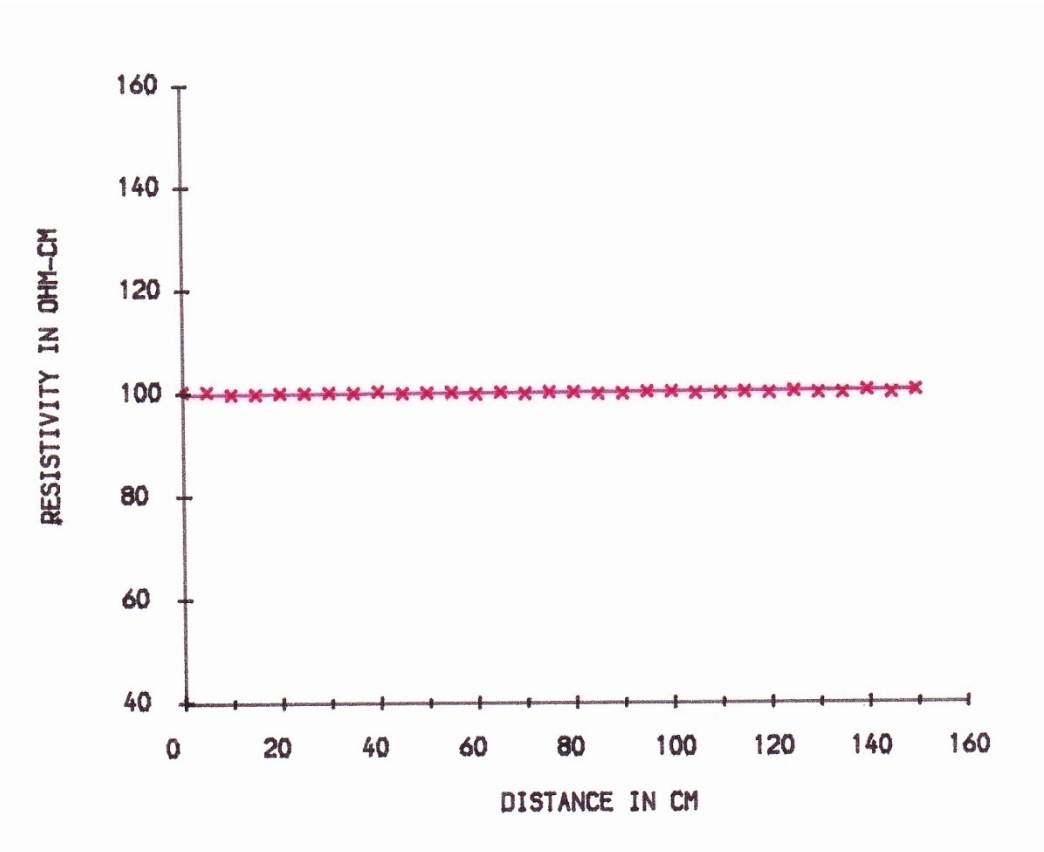

Figure 2: Resistivity of tank brine water without model illustrates the absence effect of the wall

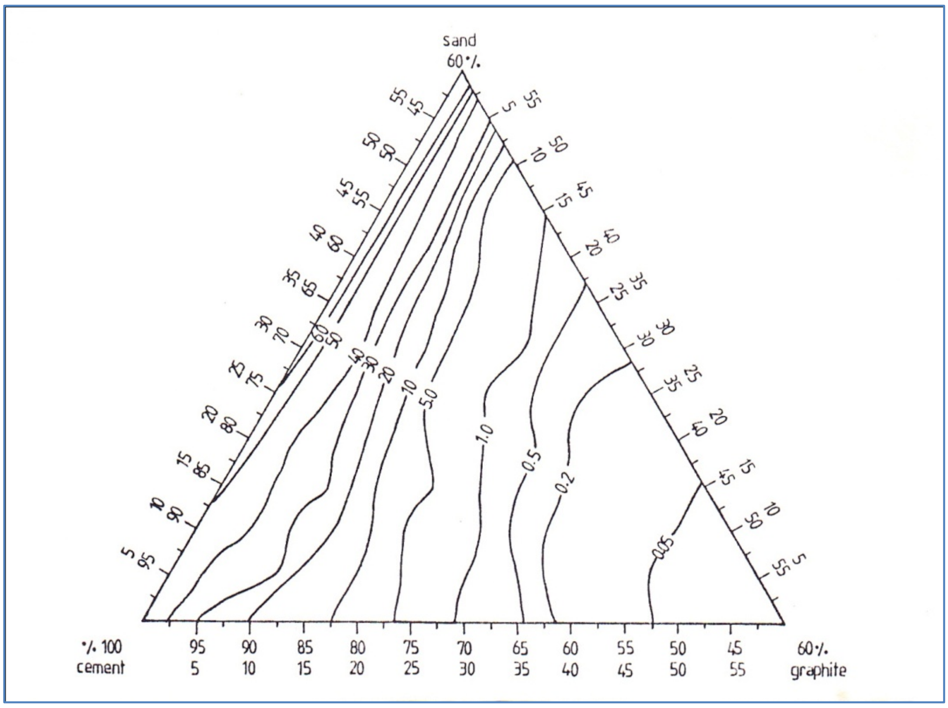

Figure 3: Formation Factor Contour Plot, Brine Res.=200ohm.cm.

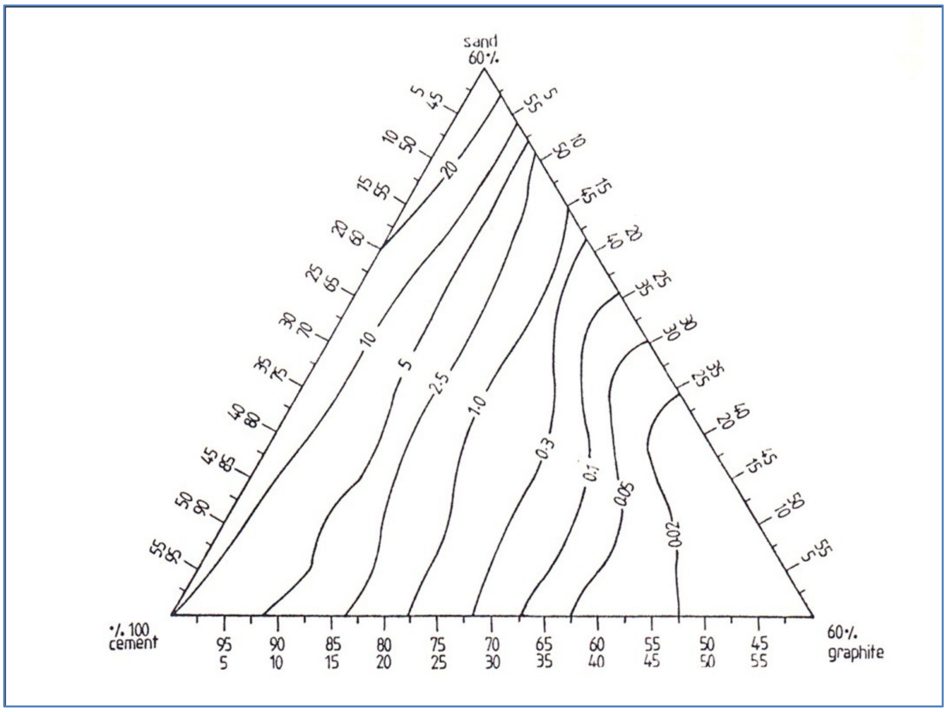

Figure 4: Formation Factor Contour Plot, Brine Res.=625ohm.cm.

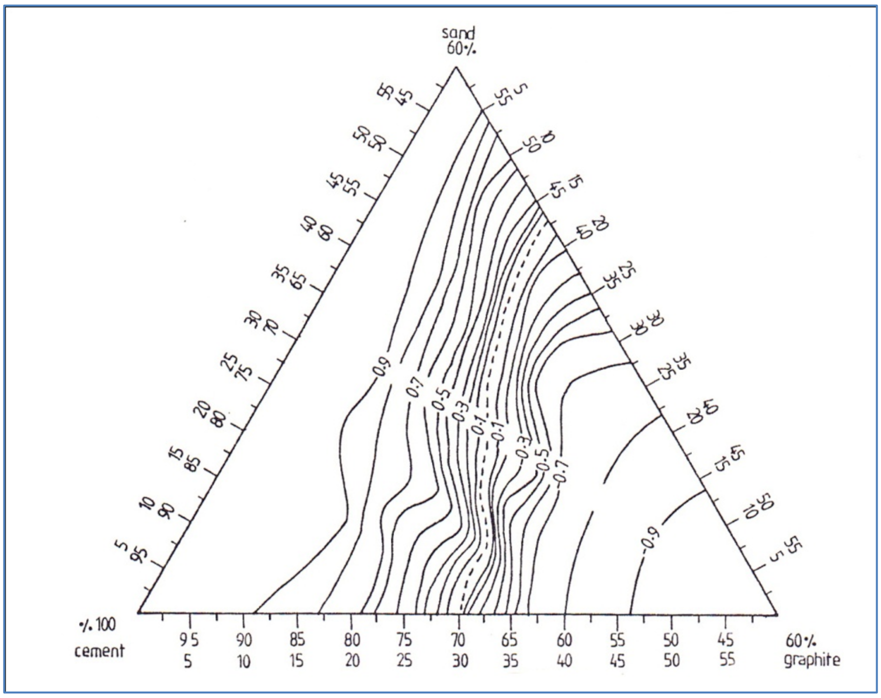

Figure 5: Resistivity Contrast Contour Plot, Brine Res.=200ohm.cm.

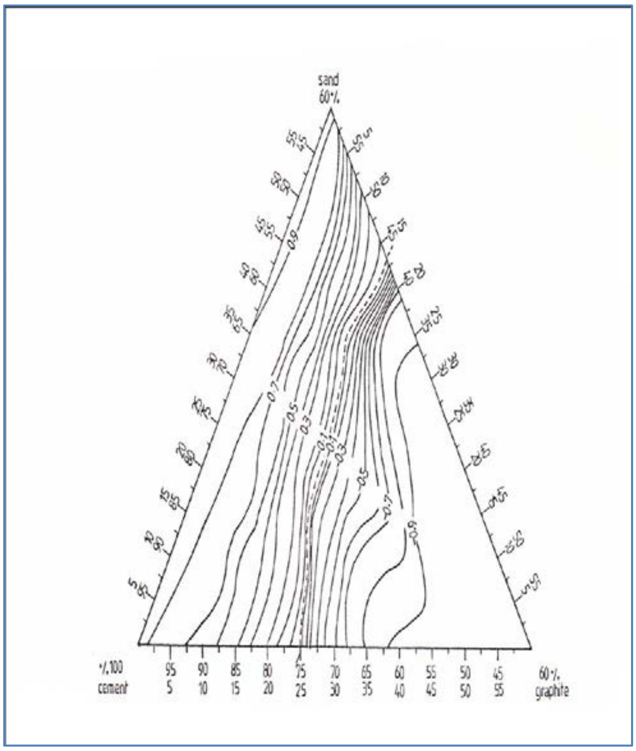

Figure 6: Resistivity Contour Plot, Brine Res.=625ohm.cm.

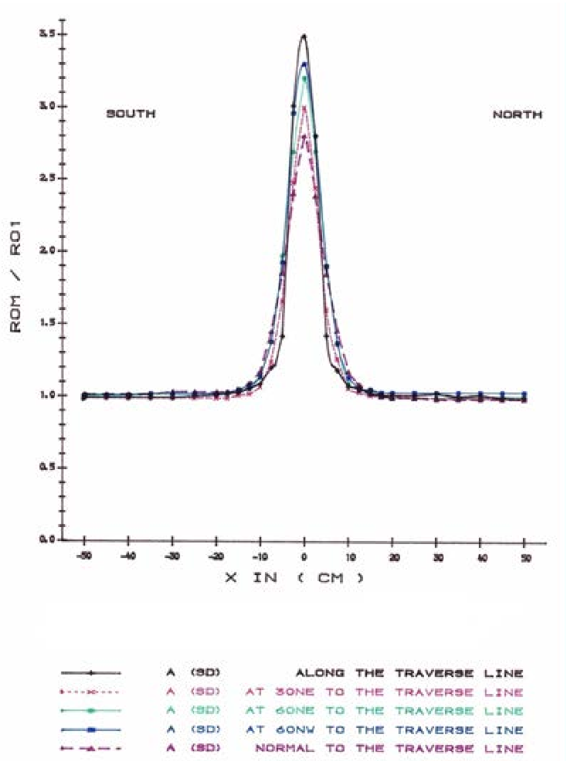

Figure 7: Rhombic App. Res. Model profile for varying system orientation, A= 5.0 CM, D= 0.5, W= 5.0, DP= 90, TON=90

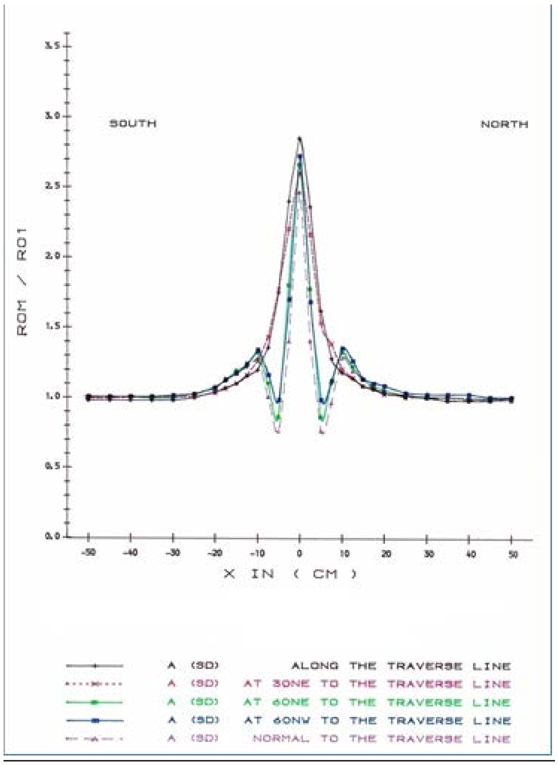

Figure 8: Rhombic App. Res. Model profile for varying system orientation, A= 10.0 CM, D= 0.5, W= 5.0, DP= 90, TON=90

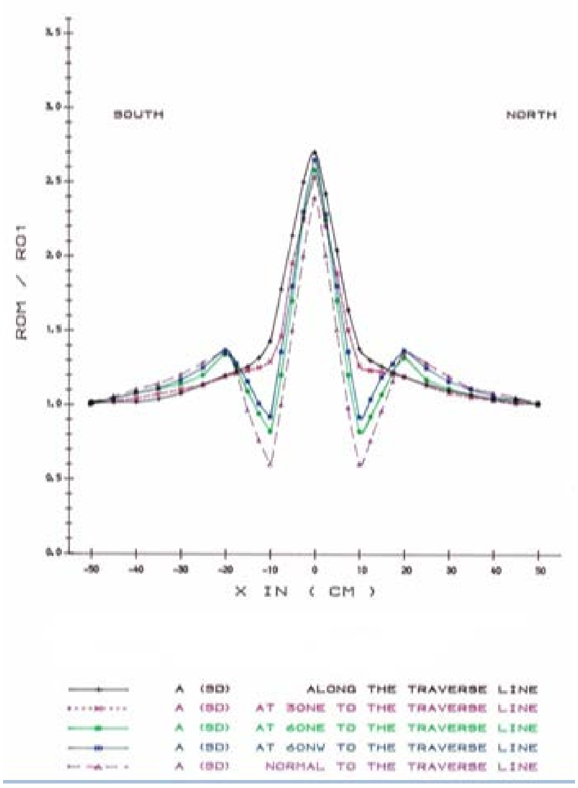

Figure 9: Rhombic App. Res. Model profile for varying system orientation, A= 20.0 CM, D= 0.5, W= 5.0, DP= 90, TON=90

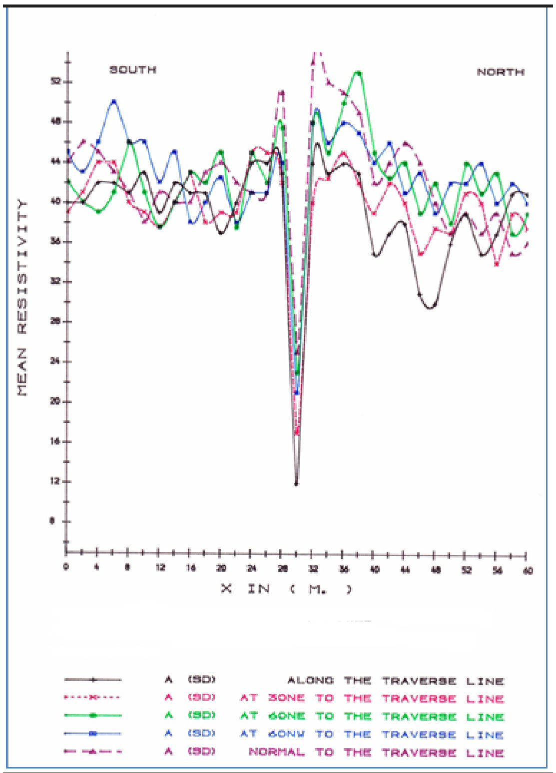

Figure 10: Rhombic App. Res. Field prof profile for varying system orientation, horsforth site **A= 1.**0 M

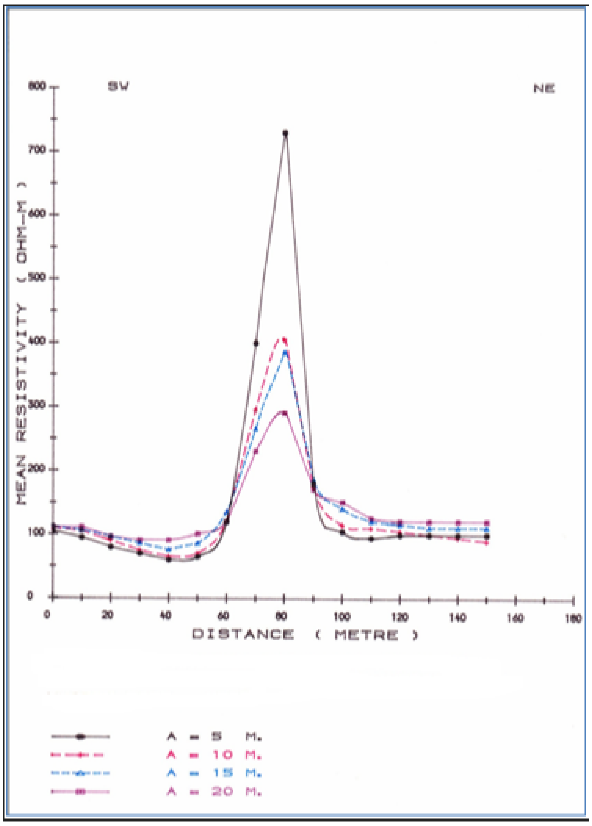

Figure 11: Rhombic electrode array with different spacing, ton= 90, traverse NO. whitby site, west

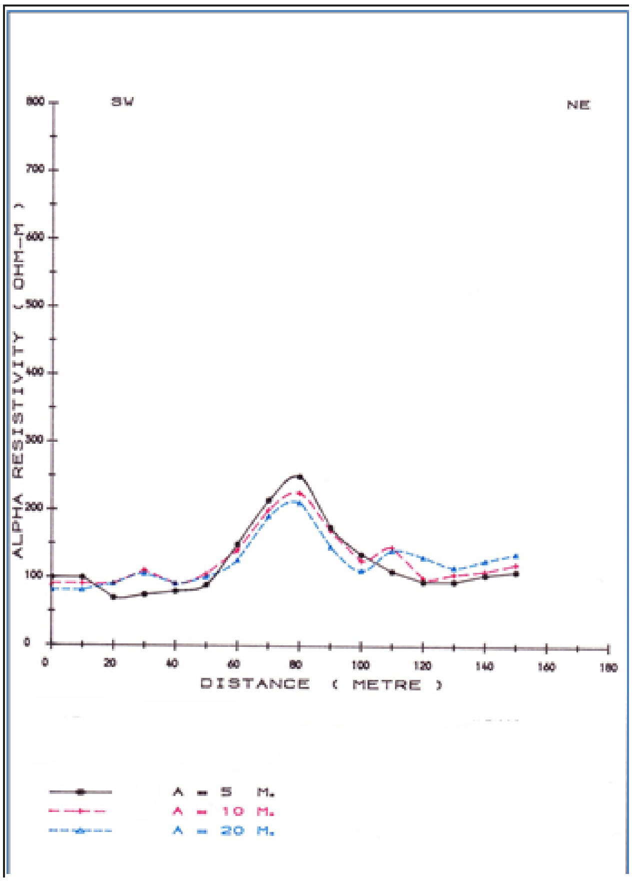

Figure 12: Wenner electrode array with different spacing, ton= 90, traverse NO. whitby site, west

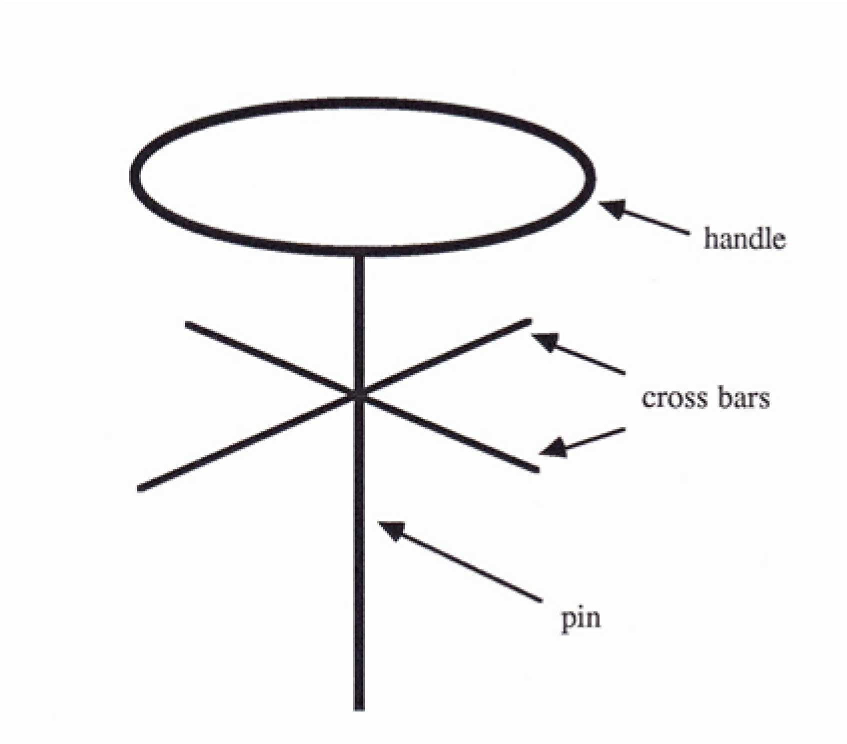

Figure 13: Schematic diagram of double – tee pin