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Hydrogeophysical Investigations in a Typical Khondalitic Terrain to Delineate the Kaolinised Layer using Resistivity Imaging

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Abstract: Investigation for high yielding water wells in the khondalitic terrain (graneti ferrous silliminite gnesiss) is mostly faced with the problem of identification of the extent of the depth of kaolinisation of the aquifer. The traditional Vertical Electrical Sounding survey, Seismic Refraction survey and Very Low Frequency Electromagnetic survey could not identify the kaolinisation of the aquifer in the present investigations. The Two Dimensional (2D) Resistivity and Induced Polarization (IP) Imaging surveys are attempted for the identification of kaolinised layer and depth of kaolinisation. Number of 2D Resistivity and IP Imaging profiles were conducted near Chipurupally in Vizianagaram district of Andhra Pradesh, India along successful and failed wells located within short distances. Resistivity and IP measurements were carried out using an ABEM SAS 4000 Terrameter. The resistivity and I.P. images have provided a clear view of the thickness of the highly weathered zone (kaolinised zone) at both successful and failed wells. The highly weathered zone is identified with the resistivity values below 25 ohm.m. The depth of highly weathered material at failed well is extended about 8-10 m more deeper than the successful wells at some places to as much as 20 m more deep at some other places. This extended deeper kaolinisation of the aquifer is responsible for failure of wells. Layers having resistivities between 25 – 65 Ohm.m are identified as aquifer layers which are composed of moderately weathered and fractured khondalitic suit of rocks (Garnti ferrous sillimanite/biotite gneiss). Layers with resistivities greater than 65 Ohm.m are interpreted to have basement characteristics belonging to the granite gneiss. Interestingly IP imaging has not provided any greater insights in delineating the kaolinistion of the aquifer when compared to resistivity Imaging, in fact resitivity imaging has shown greater depths of kaolinisation than IP Imaging.

Keywords: Khondalitic terrain, Kaolinisation of the aquifer, Resistivity and I.P. Imaging.

INTRODUCTION

In the khondalitic terrain, (garnetiferrous sillimanite/biotite gneiss), the country rock is a khondalite which is a product of high grade metamorphism of argillaceous sedimentary rocks (Krishna Rao, 1952; Krishnan, 1968). Mahadevan (1929) was the first to postulate the hydrogeological concept of the eastern ghat khondalites stating that the khondalites are altered in two different ways upon the action of water. On the surface the rock changes into lateritic soil and at the sub-surface it alters to kaoline. In this terrain well yields are high (above 8,000 LPH) where the country rock is observed to have undergone silicification. Mostly groundwater occurs in the weathered and fractured khondalite and occasionally in the basement fractures also under unconfined to semi-confined conditions. The basement rock is a granitic gneiss. The main problem in the khondalitic terrain is kaolinisation of khondalite, which is not properly being recognised in the vertical electrical sounding data. The khondalite altering partly to clay due to kaolinisation is unable to support high well yield (Venkateswara Rao, 1990). The yield might have been reduced due to infilling of fractures with kaolinite and other weathered products (Paillet, 2007). With the surface one dimensional electrical resistivity survey, it is very difficult to distinguish between kaolinised and fractured khondalite, since they show same resistivity at both the places. Therefore multi-geophysical techniques were employed in order to recognise the kaolinised layer.

EARLIER WORK

Since this paper deals with the usefulness of various geophysical techniques in hard rocks, the literature reviewed here pertains to various case studies employing multi-geophysical techniques with reference to fracture porosity mapping.

Quite a few earlier studies have used surface geophysical techniques to delineate the anisotropy of the aquifers in the hard rock terrains. Robert and Anthony (1988) have revealed that anisotropy, directional connectivity and porosity of fractured systems can be estimated from surface azimuthal electrical surveys. Hegde et al. (1989) have conducted radial vertical electrical soundings and computed coefficient of anisotropy to delineate the fractures at different horizons. The studies of Chandra et al. (1990) in the hard rocks of the Kasi-Sabarnarekha project demonstrated that the combination of resistivity profiling, Vertical Electrical Sounding (VES), Very Low Frequency Electromagnetic (VLF-EM) and Horizontal Loop Electromagnetic Profiling (HLEM) lead to the identification of maximum number of quite a good successful wells taping fractures down to a maximum depth of 230 m. Bhowmick and Renuka (1991) have opined that the weathered and fractured rocks could not be differentiated by refraction seismic survey. Chandra et al. (2002) carried out an integrated study on Vindhyan quartzite-sandstones and Dudhi granite gneisses in Sonbhadhra district of Uttar Pradesh. Their study has used a combination techniques viz. magnetic gradient, resistivity profiling and resistivity sounding with increasing current electrode separation. Venkateswara Rao (2004) has developed an improved methodology for locating potential aquifers by using resistivity, hydrogeology and geomorphic parameters. Ellefesen (2007) has reported that the S-Wave refraction profiling can be used to delineate the fractured and faulted rocks. Lee et al. (2007) have demonstrated that azimuthal self potential surveys can be successfully used to map the fractures in the bed rock and characterization of its hydraulic property.

The recent developments in the resistivity imaging techniques introduces a new era in groundwater exploration. Barker et al. (1992), Grifiths and Barker (1993), Mendoza et al. (2000), Ionnis et al. (2002), Ibrahim et al. (2003) have successfully used the resistivity imaging technique for solving geological problems in hard rock areas. Sushodhan dutta et al. (2006), Jinadasa (2009), Muralidharan et al. (2010), Tanvi Arora and Shakeel Ahmed (2010) and Kumar et al. (2010) have applied resistivity imaging techniques to delineate the aquifer zones in the hard rocks of peninsular India.

METHODOLOGY

Multi-geophysical techniques namely vertical electrical sounding, shallow seismic refraction survey, very low frequency electromagnetic survey and Two Dimensional (2D) Resistivity and Induced Polarization (IP) Imaging surveys have been employed for pairs of successful and failed wells covering khondalitic terrain where well failure is mostly due to kaolinisation. The pair of successful and failed well is selected in such a way that they are only few tens of meters apart and are in similar hydrogeologic setting.

Vertical electrical soundings were conducted with DDR2 model resistivity meter manufactured by Integrated Geo Instruments and Services Limited, Hyderabad. It has the facility to read directly the resistance offered by the formation with a voltage and current sensitivities up to one hundredth part of a milli volt and milliampere. The shallow seismic refraction was conducted by using Smartseis

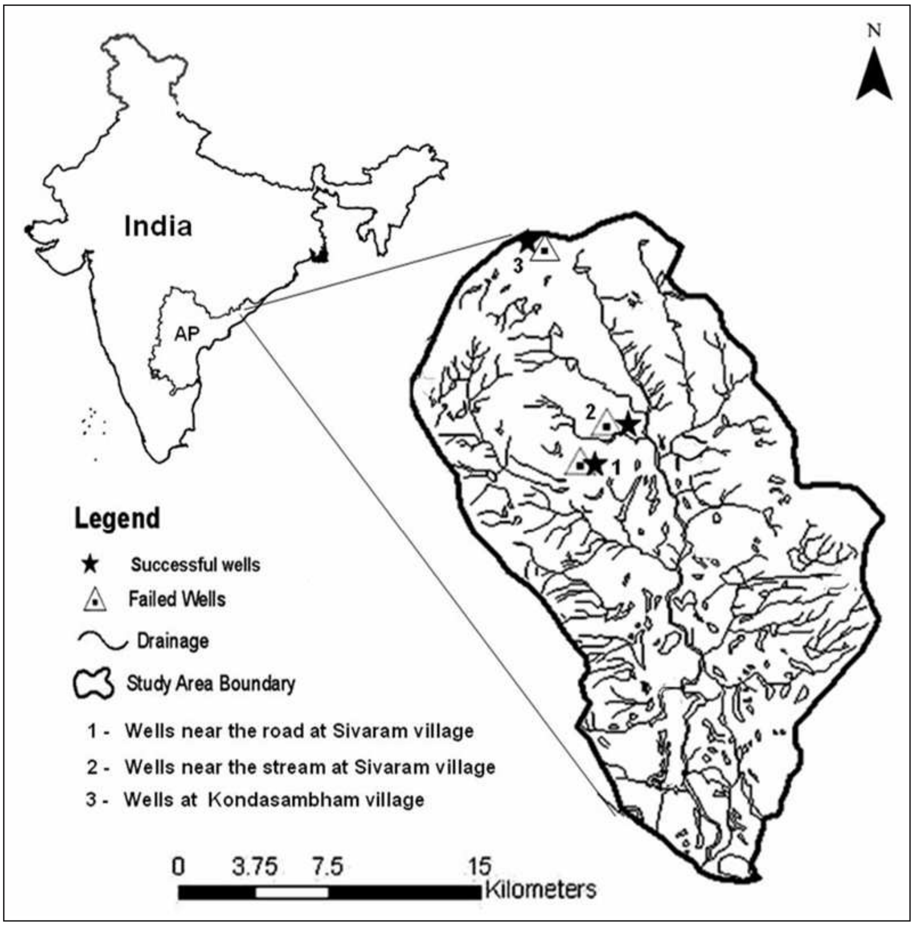


Fig.1. Location of the study area

(S-12 model) seismograph manufactured by Geometrics, U.S.A. It has 12 channels and has on field display and interpretation software to obtain velocities and thicknesses of various sub-surface layers. The Very Low Frequency (VLF) Electromagnetic survey was conducted by using WADI VLF instrument manufactured by ABEM, Sweden. This instrument detects the ratio between the secondary and primary electromagnetic fields emanated from a conductor below the ground such as a fracture zone filled with water. The higher the secondary field more the conductance. The measured electromagnetic field is converted into current densities. Resistivity and IP imaging along the profile perpendicular to the slope of the terrain was carried out at successful and failed wells using an ABEM SAS 4000 Terrameter. Here IP method is also attempted in view of its better ptential to identify the clay pockets.

The Radial Vertical Electrical Soundings were conducted at each well site in four different directions namely North-South (N-S), East-West (E-W), North-East - South-West (NE-SW) and North-West – South-East (NW-SE) directions and they are interpreted by using Inversion software (Varma and Panthulu, 1990). Similarly, seismic refraction survey was conducted in all the four directions, velocities and thicknesses of the each layer are obtained by running SIPQC software (Rimrock Geophysiscs, 1993). The software plots time distance curves, calculates layer velocities and obtain depths beneath shot points as well as geophones. VLF Electromagnetic survey was conducted in all the four directions at each well location and results are interpreted by using SECTOR software (ABEM, 1993) which computes and maps current densities with respect to depth along a profile. Measurements of Resistivity and IP imaging were interpreted using 2D inversion software (ABEM, 2009)

DISCUSSION OF THE RESULTS FROM THE CONVENTIONAL SURVEYS

In this study, a few areas were selected pertaining to the

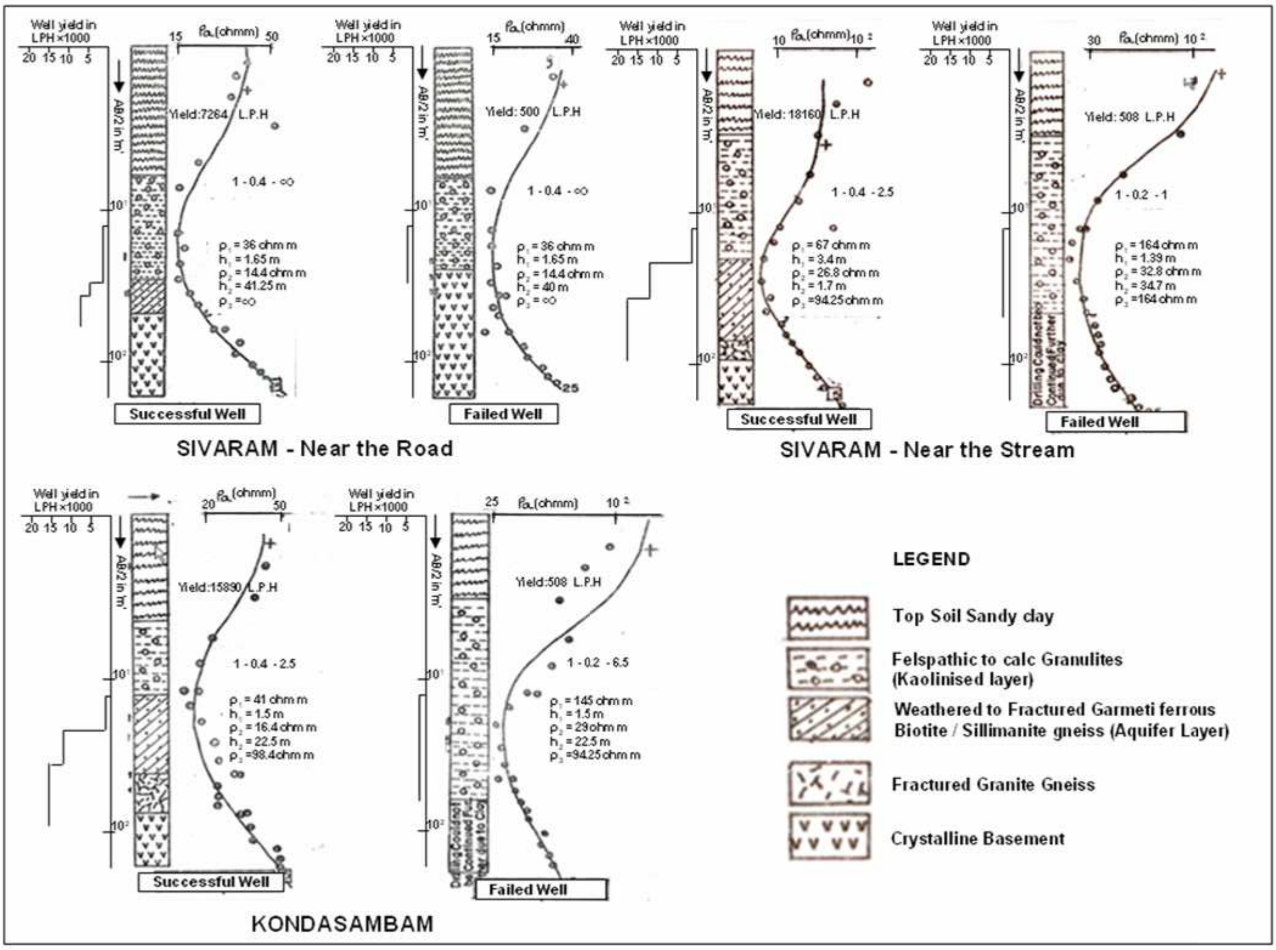


Fig.2. Vertical electrical sounding curves, yield logs and lithologs of adjacent success and failed Wells near the road at Sivaram village, near the stream at Sivaram village and at Kondasambham Village.

khondalites of northern parts of Eastern Ghats near Cheepurapalli, Vizayanagaram district of Andhra Pradesh. (Fig.1).

These areas are located near the road and near the stream of Sivaram village and near Kondasambham village where a pair of successful and failed wells occur. These pairs of successful (> 8000 LPH) and failed wells (< 600 LPH) with their lithologs, yield logs and vertical electrical sounding curves are shown in the Fig.2 and it can be observed within the pair, the difference in well yield is very large between successful and failed well. From these VES curves, it is difficult to explain differences in their well yields but actual drilling results indicate that the extent of kaolinisation as a matter of fact decides well yields. It can be observed from the lithologs (Fig.2) of the successful wells that the thickness of kaolinisation is less compared to failed wells, where the thickness of kaolinisation is more except in the pair near the road of Sivaram village. In the khondalitic terrain, it is observed by the authors that when deeper kaolinisation occurs, the kaolinised layer is followed by basement of granitic gneiss with little or no fracturing leading to the failure of wells (Venkateswara Rao and Ramadurgaiah, 2002). The failed well near the road of Sivaram village is an example. In this well the drilling has penetrated kaolinised layer, but there is hardly any improvement in the well yield because the kaolinised layer is followed by the basement without any fractures. From the yield logs (Fig.2) it is observed that most of the well yields are improved in the weathered and fractured khondalite but not in the fractured granite gneiss.

Litholog information of 42 wells drilled in the study area have been collected and the observed kaolinised layer thicknesses were analyzed by computing percentage of success wells in various ranges of kaolinised layer thickness (Table 1). From this table it can be observed that the greater the kaolinised layer thickness the lesser the success rate of the wells implying that the kaolinised layer is not supporting a good well yield. The extent of kaolinisation could not be deciphered in the VES curves interpreted with the curve matching technique and later with an inversion programme and are shown in the Table.2

Table 1. Percent Success of Wells in Various Ranges of Thickness of Kaolinised Layer

Ranges of thickness of kaolinised layer	0-10m	10-20m	20-30m	>30m
Number of successful Wells	14	8	5	0
Number of Failed Wells	3	4	4	4
Percent success	82.3	66.6	55.5	0

A comparison is made between geophysical parameters of the successful well and failed well with respect to vertical electrical sounding and seismic refraction survey (Table.2). While we have already noted that the VES has not adequately delineated the kaolinised layer, therefore, the seismic refraction survey is attempted to delineate the kaolinised layer with an assumption that the differences in their wave velocities between kaolinised layer and fractured layer may identify the kaolinised layer. But from Table 2, it can be observed that the seismic refraction survey also could not delineate the kaolinised layer separately but it has shown kaolinised layer, weathered and fractured zone as a single unit. Then, electromagnetic survey is attempted whose results are dipicted in Fig. 3 and Fig. 4.

Vertical cross section of the electromagnetic data in the perpendicular directions to the slope at successful and failed wells is displayed in the form of current densities with respect to depth. The conductivity of the formation is identified with the intensity of the black shade i.e., the more the black shade the more the conductivity of the formation. From these figures it can be observed that there is no clear geophysical signature that can differentiate the kaolinised layer from the fractured layer.

Again an attempt is made to prepare apparent resistivity polygons, which are prepared by connecting apparent resistivity values in all the four directions for a particular electrode spacing (AB/2) as shown in Fig. 5.

The directions along which the VES were conducted are N-S, E-W, NE-SW and NW-SE. In every VES, the maximum

Table 2. Resistivities and Velocities of the subsurface formations below Success and Failed wells in Khondalitic terrain

Location of	Resistivity Data (ρ in 'Ω.m' , h in 'm')				Seismic Refraction Data (v in m/s)			
the well	Success Well		Failed Well		Success Well		Failed Well	
Sivaram- Near the Road	ρ_1 = 34.74 ρ_2 = 14.23 ρ_3 = 1004.2	h_1 = 2.43 h_2 = 26	ρ_1 = 39.60 ρ_2 = 13.96 ρ_3 = 1009.27	h_1 = 1.55 h_2= 37.95	v_1 = 546 v_2 = 1453 v_3 = 5276	h_1 = 5.5 h_2 = 14.0	v_1 = 2009 v_2 = 2552	h_1 =7.0
Sivaram- Near the Stream	ρ_1 = 82.91 ρ_2 = 14.96 ρ_3= 457.39	h_1 = 1.93 h_2 = 33.48	ρ_1 = 46.43 ρ_2 = 21.76 ρ_3 = 999.0	h_1 = 2.79 h_2= 32.60	v_1 = 770 v_2 = 1667 v_3 = 2564	h_1 = 9.5 h_2 = 10.0	v_1 = 592 v_2 = 1942 v_3 = 3846	h_1 =5.5 h_2=12.0
Kondasambham	ρ_1 = 41.0 ρ_2 = 16.4 ρ_3 = 98.4	h_1 = 1.5 h_2 = 22	ρ_1 = 145.0 ρ_2 = 29.0 ρ_3 = 94.25	h_1 = 1.5 h_2 = 22.5	v_1 = 422 v_2 = 2488	h_1 = 6.5	v_1 = 535 v_2 = 1616 v_3 = 6250	h_1 =6.0 h_2=18.0

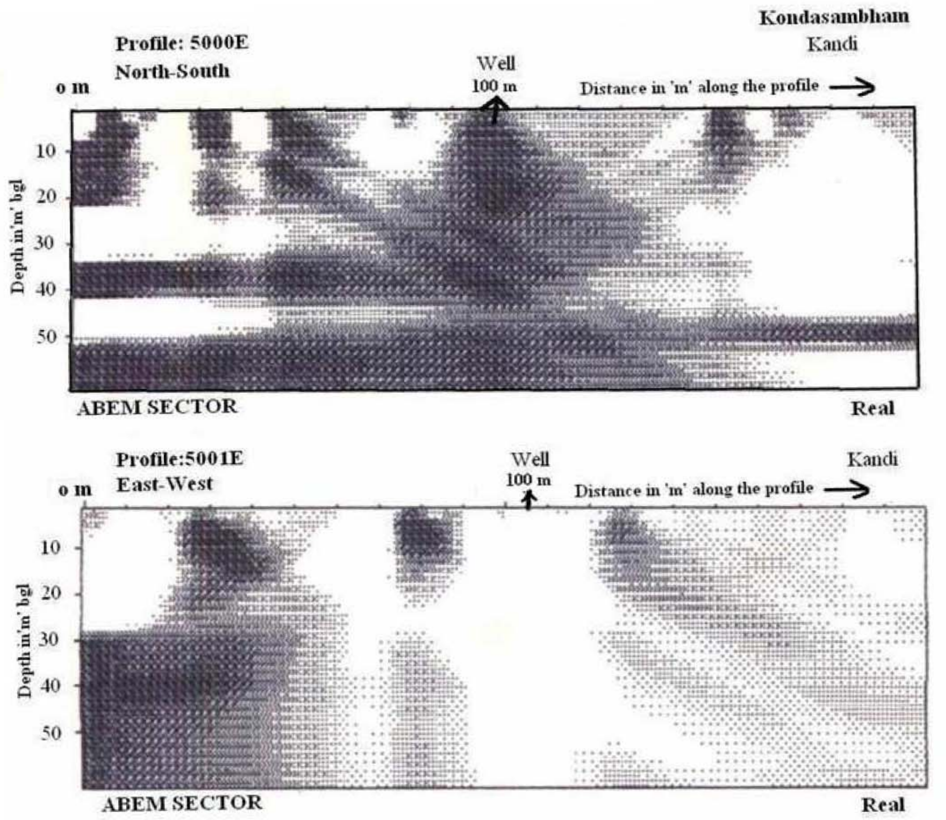


Fig.3. Vertical cross section of VLF Electromagnetic data of a failed well at the Kondasambham village.

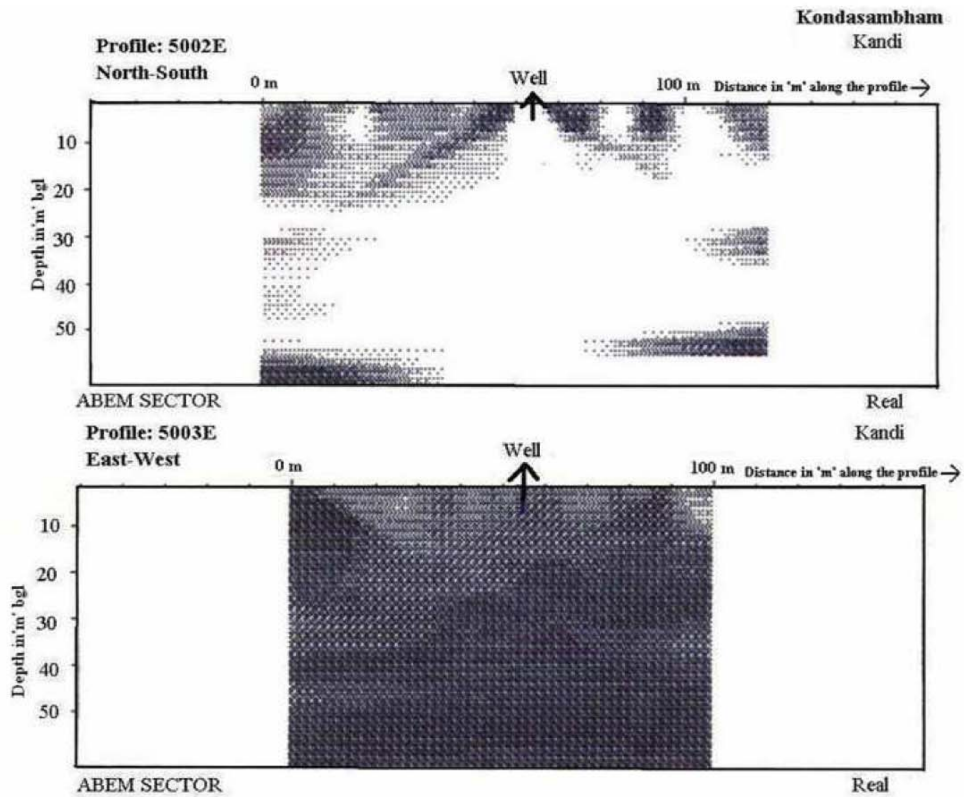
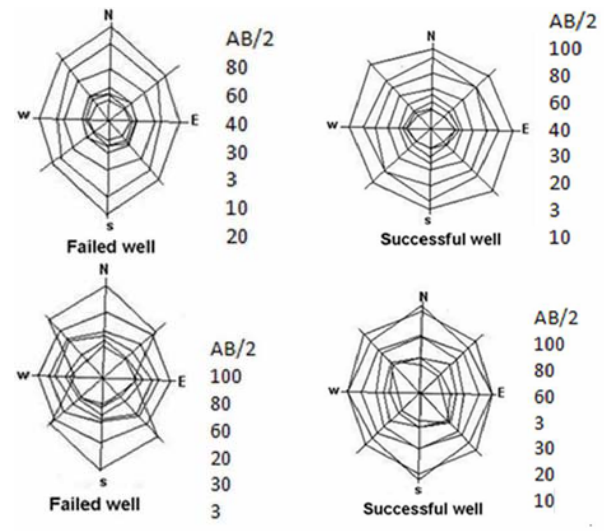


Fig.4. Vertical cross section of VLF Electromagnetic data of a successful well at the Kondasambham village.



Note: The AB/2 values represent electrode spacing in Schlumberger configuration at which apparent resistivities are measured. The outer most polygon represent the apparent resistivity magnitude at respective directions at the top value of the AB/2 column. Similarly, the inner most polygon represent the bottom most value of AB/2 column

Fig.5. Apparent resistivity polygons of the wells at the Sivaram village

AB/2 is 100 m. For a particular AB/2, the apparent resistivities are more or less the same in almost all directions for successful wells, while, the same is not true for failed wells. In the case of failed wells, the apparent resistivities are differing substantially from the AB/2 = 30 m onwards. Here successful wells and failed wells are differentiated by displaying less anisotropy (rounded nature of the polygons) for successful wells and more anisotropy (elongated in a particular direction) for failed wells. It means that less kaolinisation and more water bearing weathered and fractured khondalite is indicated by less anisotropic nature while more kaolinised and less water bearing formations of the weathered and fractured khondalite is indicated by more anisotropic nature in the apparent resistivity polygons (Venkateswara Rao, 2011). The apparent paradox may be explained by the fact that the khondalitic formation is sedimentary in origin and it is not behaving like a real hard rock, particularly when it is partly kaolinised. When the rock is intensely kaolinised, in one direction it shows more kaolinisation and in another less kaolinisation thereby leading to more anisotropy than normal weathered khondalite. Since the process of conducting Radial Vertical Electrical Sounding is cumbersome in the field and does not provide the depth section to guide the drilling process, 2D Resistivity and IP Imaging Surveys are conducted at successful and failed wells.

2D Resistivity and IP Imaging

Unlike conventional resistivity sounding and lateral profiling surveys, 2D resistivity imaging is a fully automated technique that uses a linear array of about 48 electrodes (In the present survey) connected by multicore cable. The current and potential electrode pairs are switched automatically using a control module connected to a resistivity meter (that provides the output current). In this way a profile of resistivity against depth (pseudosection) is built up along the survey line. Data is collected by automatic profiling along the line at different electrode separations. The computer initially keeps the spacing between the electrodes fixed and moves the pairs along the line until the last electrode is reached. The spacing is then increased

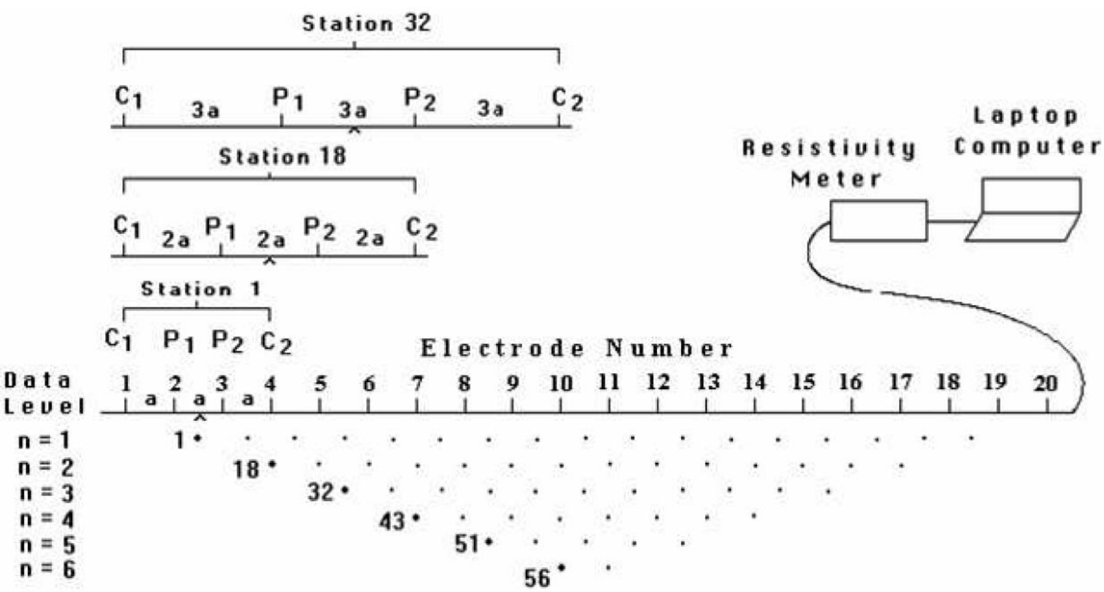


Fig.6. Sequence of measurements in resistivity imaging to build up a pseudosection

by the minimum electrode separation and the process is repeated in order to provide an increased depth of investigation (Fig. 6). The maximum depth of investigation is determined by the spacing between the electrodes and the number of electrodes in the array. For a 48 electrode array with an electrode spacing of 5m this depth is approximately 40 m. in the present survey. The raw data is initially converted to apparent resistivity values using a geometric factor that is determined by the type of electrode configuration used. Once converted the data is modeled using finite element and least squares inversion methods in order to calculate a true resistivity versus depth pseudosection by using 2D Resistivity inversion software. The same procedure is repeated for IP measurements also.

2D Imaging Profiles

The imaging profiles are laid across the slope of the ground where the successful or failed wells are located and these wells are almost in the middle of the profile. The Resistivity and I.P. Imaging profiles conducted adjacent to the successful and failed wells are shown in Fig. 7 to Fig. 9 (only resistivity images are shown). For the convenience of interpretation various layers and their thicknesses have been identified from the resistivity images and are tabulated at each image (Figs. 7 to 9).

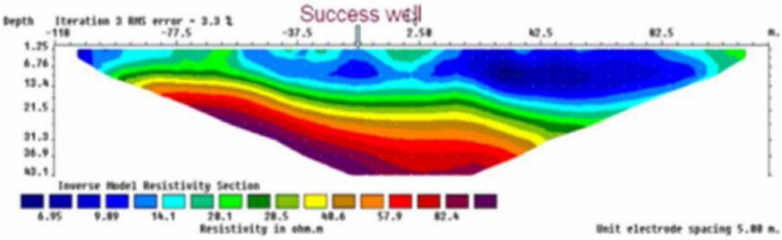
From these figures it can be observed that the formations below the failed wells have become kaolinized to deeper depths, compared to successful wells. For instance, the depth of kaolinisation at failed well near the road of Sivaram village is nearly 8 m. more than the depth of kaolinisation at successful well (Fig.7). The same for the well pair near the stream of the Sivaram village is 21.5 m (Fig.8). This extended deeper kaolinisation of the formations is responsible for the failure of the wells. The resistivity image for the failed well in the Fig.8 has low resistive concentric contours in the middle of the image which is interpreted as kaolinised pocket and has given well supportive scientific data for the possible explanation for the failure of the well which is aptly supported by the drilling results. This kind of spatial distribution of clay pocket obtained in the imaging cannot be accomplished in the one dimensional VES data. In fact, actual kaolinisation depths obtained from drilling results are more when compared to resistivity and I.P. survey results.(Table 3). In this table, the depths of kaolinisation is taken as the depth at which kaolinisation layer ends in the image. It is because, above the kaolinised layer, there are only a few meters of soil layer. The kaolinised layers are identified with the help of resistivity images where all the formations whose resistivity is less than 25 Ohm.m. are considered as kaolinised formations and are shown in bold letters in the table inserted at respective images (Figs.7 to 9). Layers having resistivities between 25 – 65 Ohm.m are identified as aquifer layers which are composed of moderately weathered and fractured khondalitic suite of rocks. Layers with resistivities greater than 65 Ohm.m are interpreted to have basement characteristics belonging to the granite gneiss. It is also observed that the thickness of various layers obtained in the images are not matching properly with the drilling results. But in the overall context at each pair of successful well and failed well, the failed well images have shown greater depths of kaolinisation which is responsible for failure of wells. Between I.P. and Resistivity Imaging methods, resistivity Imaging method has shown greater depths of kaolinisation and lower resistivity range than the I.P. method (Table 3). Therefore, the Resistivity Imaging method is recommended to identify the kaolinisation.

CONCLUSIONS

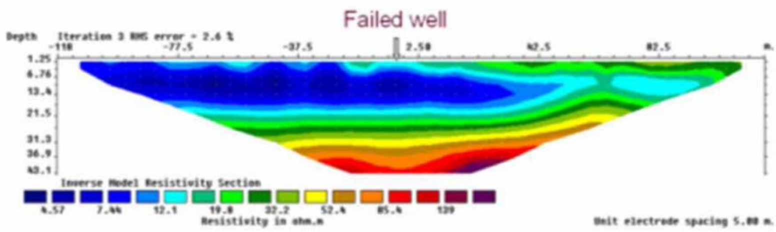
The resistivity and I.P. images have provided a clear view of the thickness of the highly weathered zone (kaolinised zone) at both successful and failed wells. The highly

Table 3. Depths of kaolinization of the formations at Successful and Failed Wells

Location of the well	Depths of Kaolinization in 'm'						Resistivities of the Kaolinized Layer in 'Ohm.m'			
	Success Well			Failed Well			Success Well		Failed Well	
	Resistivity Method	I. P. Method	Drilling Results	Resistivity Method	I.P. Method	Drilling Results	Resistivity Method	I.P. Method	Resistivity Method	I.P. Method
Sivarm near the road	17.4	17.4	25	25.0	26.0	23.0	20.1	17.3	19.8	19.0
Sivaram near the Stream	21.5	13.4	16	43.0	43.1	Kaolinization extended to greater depths	16.7	15.0	17.3	20.0
Kondasambham	11.0	9.94	12.0	21.5	17.6	Kaolinization extended to greater depths	16.8	23.5	24.0	25.8

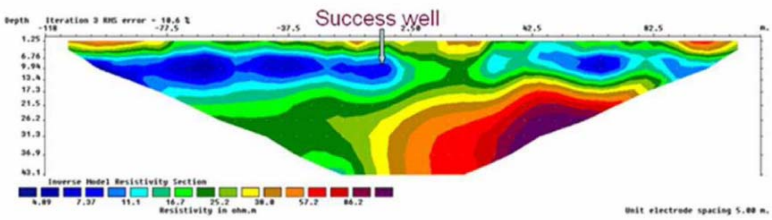


Depth in (m)	Resistivity (Ohm.m)
0 – 10.08	9.89
10.08 – 13.4	**14.1**
13.4 – 17.45	**20.1**
17.45 – 21.5	28.5
21.5 – 26.4	40.6
26.4 – 31.3	57.9
31.3 – 39.0	82.4

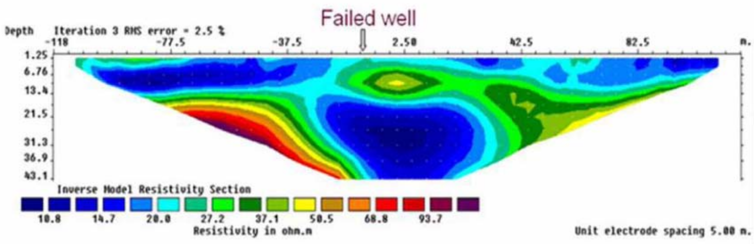


Depth in (m)	Resistivity (Ohm.m)
0 – 20.5	**4.57 - 12.1**
20.5 – 25.0	**19.8**
25.0 – 43.1	26 - 85

Fig.7. Electrical Resistivity images at Successful and Failed Wells near the road of Sivaram village.

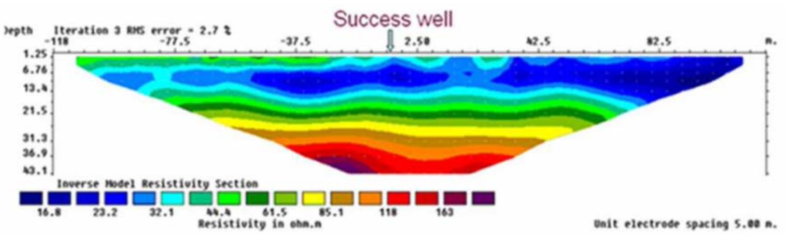


Depth in (m)	Resistivity (Ω.m)
0- 4	25.2
4 – 6.76	**16.7**
6.76 - 12.0	**7.37**
12 – 17.3	**11.1**
17.3 – 21.5	**16.7**
21.5 – 25.2	25.2
25.2 – 43.1	38.0

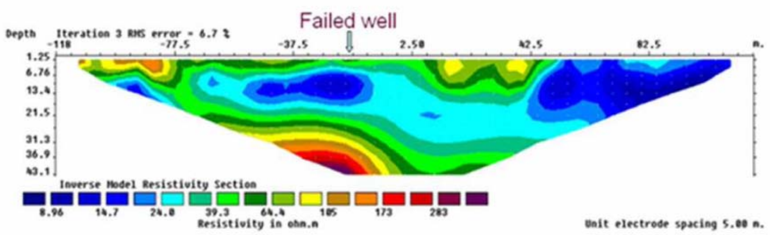


depth in (m)	Resistivity (Ω.m)
0 – 13.0	27.2
13 – 15.5	**20.0**
15.5 – 39.0	**14.7**
39.0 – 43.1	**17.3**

Fig.8. Electrical Resistivity images at Successful and Failed Wells near the stream of Sivaram village.



Depth in (m)	Resistivity (Ω.m)
0 – 11.0	**16.8**
11 – 15.5	32.2
15.5-19.48	44.4
19.48– 25	61.5
25 – 31.3	85.1
31.3 -40.0	118
40 – 43.1	163



Depth in (m)	Resistivity (Ω.m)
0 – 1.25	64.4
1.25 – 4.0	39.9
4.0 – 6.76	**24.0**
6.76 – 15.5	**14.7**
15.5 – 21.5	**24.0**
21.5 – 26.4	39.3
26.4 – 31.5	64.4
31.5 – 36.0	105
36 – 42.0	173

Fig.9. Electrical Resistivity images at Successful and Failed Wells at the Kondasambham Village.

weathered zone is identified with the resistivity values below 25 ohm m. The depth of highly weathered material at failed well is extended about 8-10 m more deeper than the successful wells at some places and to as much as 20 m more deep at some other places. This extended deeper kaolinisation of the aquifer is responsible for the failure of wells. Layers having resistivities between 25 – 65 Ohm.m are identified as aquifer layers which are composed of moderately weathered and fractured khondalitic suite of rocks. Layers with resistivities greater than 65 Ohm.m are interpreted to have basement characteristics belonging to the granite gneiss. Interestingly IP imaging has not shown any greater insights in delineating the kaolinisation at depths when compared to resistivity imaging which has shown greater depths of kaolinisation. The conventional vertical electrical sounding, the seismic refraction and VLF electromagnetic methods could not differentiate between successful and failed wells. However, the resistivity polygons prepared with the radial vertical electrical sounding data has revealed some difference between successful wells and failed wells. Since the kaolinised depths cannot be estimated from these resistivity polygons and conducting of radial vertical sounding is time consuming, the two dimensional resistivity imaging method is recommended for the delineation of kaolinised zones.

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