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Azimuthal square array resistivity studies to infer active fault zones in the areas of known seismicity, Kottayam District, Kerala - A case study

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ABSTRACT
The earthquakes in Kerala are restricted between NNW-SSE and NE and SW trending fault and fracture system. Correlation of earthquake events has close proximity to the lineaments. To compare the seismic activities with the fracture patterns, depth wise resistivity structures of fault / fracture and horizontal conductivity zones and their orientation are detected using Square Array resistivity (dc) technique in Edamarugu, Rendatrumukku and Valliapara of Kottayam district, Kerala. The square array sounding requires 65% less surface area than Wenner or Schlumberger technique and records the regional bedrock anisotropy. The heterogeneities obscured due to the variations of bed rock, relief and placement error are overcome by the higher apparent anisotropy measured by square array. The apparent resistivity obtained from the square array technique are plotted as Azimuthal Polar plots, Cartesian Azimuthal graphs and depth sounding curves to scan the depth wise fracture/ fault orientation and gliding plane. The conductivity strikes identified from these plots have been categorized as primary, secondary and tertiary conductive and resistive zones. The horizontal permeable zones independent of direction have been identified at various depths. The detection of the fault/fracture zone with low resistivity values has greater significance in seismological studies. Prominent resistivity lows correlated with seismically activated fault zones in the study area are discussed in detail.

INTRODUCTION

Geophysical study on the natural fault system is warranted to improve the understanding on the physics of faulting and the associated earthquakes. The determination of the strength and frictional behaviour of the fault, orientation of bedrock fracture are important ingredients in improving our ability to forecast earthquake occurrence and to anticipate the severity of earthquake damage (Hickman, Zoback & Benoit 1998). Before making attempts of earthquake prediction, it is utmost important to concentrate on the general tectonic setting of the area. The earthquakes in Kerala are restricted between NNW-SSE and NE and SW trending faults and fractures. It shows that the lineaments have strong control on the drainage patterns in Kerala. Analysis of seismic pattern of an epicentral distribution of 52 earthquakes in Kerala for the past 185 years from 1823 to 2003 is bounded between NE-SW and NW-SE trending lineaments. Gelfand et al., (1972) has identified the intersection of fractures / lineaments as nodal region or knot along which the stored up stress energy is discharged in the form of seismicity. The lineaments have close association with earthquake epicenters in Kerala. Out of 31 earthquakes occurred, twenty two are found in closer to nine lineaments (Ganesha Raj et al., 2001; Bhattacharya 2003).

The energy built up through the fractures/fissures, was discharged in the form of seismicity of small magnitude in earthquake prone areas of Kerala. The seismic belts consist of large families of faults and glide planes, which make the shearing motion along the belts easier. The intersection of faults/lineaments interrupts easy gliding in both directions and augments the hardening rates and cumulates the higher potential energy. As the external stresses from neighbouring and remote regions are transmitted towards the intersection points, it becomes kernel (Tan et al., 1987).

Three experimental sites viz., Edamarugu (Latitude: 9°44’31.6"N - Longitude: 70°46’14.0"E.), Rendatrumukku (Latitude: 09°42’39.6" N – Longitude: 76°47’05.9" E) and Valliapara (Latitude: 09°41’40.4" N – Longitude: 76°43’50.7" E) in Kottayam districts are selected on the basis of identification of linear features and intersections of faults from imageries and seismotectonic map followed by field check up (Fig.1). The surface geophysical study in these areas has been carried out to make depthwise anisotropy resistivity image of vertical and horizontal fracture / fault orientations. Earthquakes and tremors occurred in the study area and other nearby areas of Changanacherry-Karukachal – six times, (1821, 1823, 1841, 1849, and 1856), Kottayam - three times (1953, 2000, 2003); Erattupetta - three times (2000, 2001, 2003) with magnitudes ranging from M 3.3 to M 5.0. Intersection of NW-SE and NE- SW trending faults are observed at first experimental site Edamarugu. The second experimental area; Rendatrumukku is at the junction of E-W and N-S trending faults. The third site Valliapara is located on the banks of Meenachil River. The NE-SW trend of the river is offset at two places within a 5 km distance. Charnockite, Khondalites and Gneiss are the main rock types. Emplacement of NW-SE trending dyke of 81 Ma age is found between Edamarugu and Rendatrumukku indicates the igneous episode in this area.

AZIMUTHAL SQUARE ARRAY (DIRECT CURRENT) RESISTIVITY SURVEYS AND DATA COLLECTION

Azimuthal square array (dc) resistivity is a modified resistivity method, wherein the magnitude and directions of the electrical anisotropy are determined. An electrode array is rotated about its center so that the apparent resistivity is observed for several directions (Taylor & Fleming 1988). The side length of the square is defined as spacing 'a' and is equal to the depth of penetration (Degnan, More & Mack 2001). The array is expanded symmetrically about the centre point with an increment in 'a' spacing by $(2)^{1/2}$. The square array sounding technique requires 65% less surface area than the Wenner or Schlumberger technique (Habberjam & Watkins 1967).This technique is about twice as sensitive to anisotropy as linear array. This azimuthal square array study was carried out at the three experimental sites Edamarugu, Rendatrumukku, Valliapara from 19 to 26th November 2003; with CRM 500 Resistivity meter, steel electrodes and connecting cables.

DATA ACQUISITION OF APPARENT RESISTIVITY FROM SQUARE ARRAY METHOD

The starting orientation of square array is aligned in N-S direction. The apparent resistivity is measured from perpendicular sides (alpha and beta) and diagonal (gamma) of each square (Fig.2).

In each of the three experimental sites, azimuthal square array soundings were carried out for alpha, beta and gamma array orientations (Fig.2). Depth wise apparent resistivity was obtained by varying spacing between 20-400m, at an interval of 20m, which resulted in twenty azimuthal squares with the each of the orientations. The same procedure is repeated for alpha', beta' and gamma' configurations also (Fig.2).

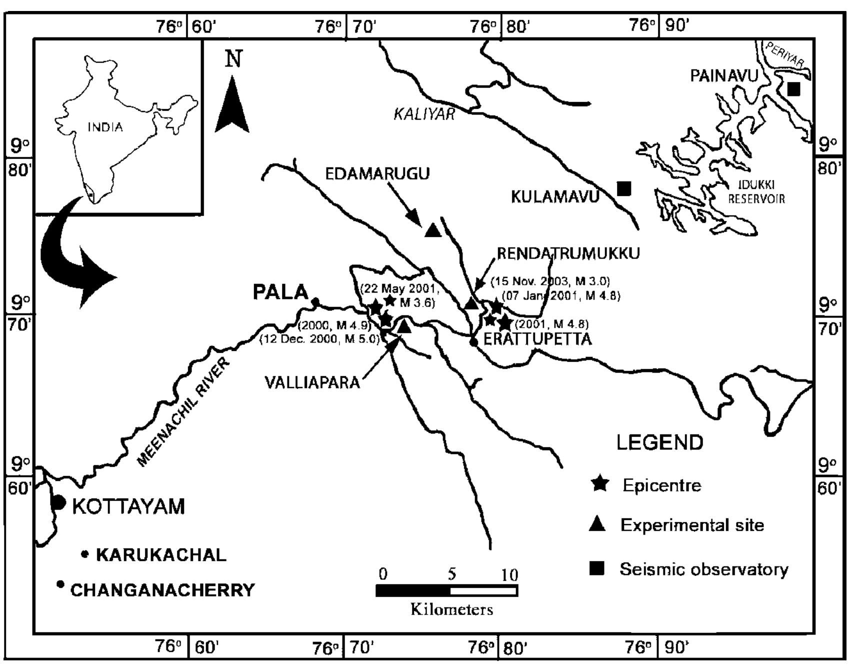

Figure 1. Location map of the study area, Erattupetta, Kottayam District, Kerala

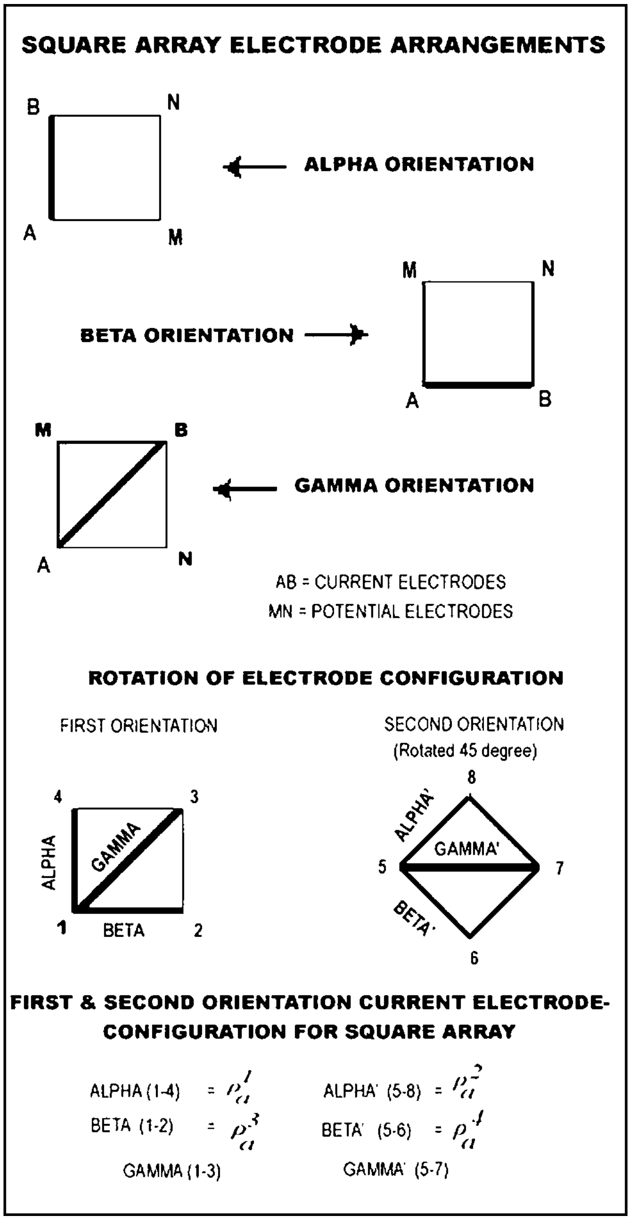

Figure 2. Electrode arrangements for square array (dc) resistivity method.

Thus, at each site 120 apparent resistivity measurements are made and in total 360 apparent resistivity data are generated for the three experimental locations. The apparent resistivity for square array is determined by using the formula given below.

Apparent resistivity

$$\rho_a = \frac{K\Delta V}{I} \qquad \text{......... (1)}$$

Where ρ_a = apparent resistivity;
K = geometric factor for the array;
V = potential difference, in volts; and
I = current magnitude, in amperes.

The geometrical factor (K) for square array is calculated by using the formula

$$K = \frac{2\pi a}{2-(2)^{1/2}} \qquad \text{......... (2)}$$

Where 'a' = square-array side length, in meters (Habberjam & Watkins 1967)

Habberjam (1972) derived the following expression for the variation of apparent resistivity with square array orientation:

$$\rho_a = \frac{\rho_m}{2-(2)^{1/2}}\left(\frac{2}{[1+(N^2-1)\cos\theta^2)^{1/2}]}\right)-\left(\frac{1}{[2+(N^2-1)(1+\cos 2\theta)^{1/2}]}\right)-\left(\frac{1}{[1+(N^2-1)(1-\sin 2\theta)^{1/2}]}\right).(3)$$

Where

ρ_m = $[(\rho_a^{\alpha})(\rho_a^{\beta})]^{1/2}$ apparent resistivity perpendicular to fractures;
ρ_a^{l} = apparent resistivity parallel to fractures;
ρ_a^{α} = apparent resistivity measured in alpha direction
ρ_a^{β} = apparent resistivity measured in beta direction
θ = angle measured from azimuth of current electrodes to fracture strike;
N = effective vertical anisotropy = $[(1+\lambda^2-1)\sin\alpha^2)^{1/2}$;
λ = coefficient of anisotropy; $\lambda=(\rho_a^{\perp}/\rho_a^{ll})^{1/2}$
$\rho_a^{\perp}$ = apparent resistivity measured perpendicular to fracture strike
ρ_a^{ll} = apparent resistivity measured parallel to fracture strike
a = dip of fractures.

The angle measured from the azimuth of current electrodes to fracture strike *(θ)* is calculated by

$$\theta = \frac{1}{2}\tan^{-1}\left[\frac{(D^{-2}-C^{-2})}{(A^{-2}-B^{-2})}\right] \qquad \text{......... (4)}$$

Where

A = $[(\rho_a^3+3\rho_a^1)/2+(\rho_a^4+\rho_a^2)/(2)^{1/2}][2+(2)^{1/2}]$;
B = $[(\rho_a^1+3\rho_a^3)/2+(\rho_a^2+\rho_a^4)/(2)^{1/2}][2+(2)^{1/2}]$;
C = $[(\rho_a^4+3\rho_a^2)/2+(\rho_a^1+\rho_a^3)/(2)^{1/2}][2+(2)^{1/2}]$;
D = $[(\rho_a^2+3\rho_a^4)/2+(\rho_a^3+\rho_a^1)/(2)^{1/2}][2+(2)^{1/2}]$;

with

ρ_a^1 = apparent resistivity measured along the alpha direction
ρ_a^2 = apparent resistivity measured along the alpha' direction
ρ_a^3 = apparent resistivity measured along the beta direction
ρ_a^4 = apparent resistivity measured along the beta' direction

In the square array the apparent anisotropy (λ_a) is measured between ratios of apparent resistivity measured perpendicular to fracture strike (ρ_a^{l}) to apparent resistivity measured parallel to fracture strike (ρ_a^{ll}) and is given by

$$\lambda_a = \frac{\rho_a^{\perp}}{\rho_a^{ll} I} = \frac{N[(N^2+1)^{1/2}]}{[(N^2+1)^{1/2N}]} \quad \text{......... (5)}$$

Where N = bedrock anisotropy.

$$N = [(T+S)/(T+S)]^{1/2} \quad \text{......... (6)}$$

With $T = A^{-2}+B^{-2}+C^{-2}+D^{-2}$;

$S = 2\ [(A^{-2}-B^{-2})^2 + (D^{-2}-C^{-2})^2]^{1/2}$

Data generated for bed rock anisotropy (N) and apparent anisotropy (λ_a) with the help of equations (5) and (6) and are utilized to construct (Fig.3) to characterize the anisotropism of bedrocks in the three study areas. Plotting of data of the bedrock anisotropy (N) versus apparent anisotropy (λ_a) show high upward trends. The higher apparent anisotropy measured by square array is an advantage because the anisotropy is less likely to be obscured by heterogeneities in bed rock or overburden, relief or electrode placement error (Habberjam 1972; LeMasne 1979; Darboux-Afouda & Louis 1989) than the other electrodes arrays like Wenner or Schlumberger.

DEPTH WISE ANALYSIS OF THE FAULT / FRACTURE TRENDS IN THE STUDY AREA

The apparent resistivity values calculated for the study areas viz; Edamarugu, Rendatrumukku and Valliapara are plotted as Azimuthal Polar plots, Cartesian Azimuthal graphs and depth sounding plots to detect depths of the fault/fracture orientations and gliding planes.

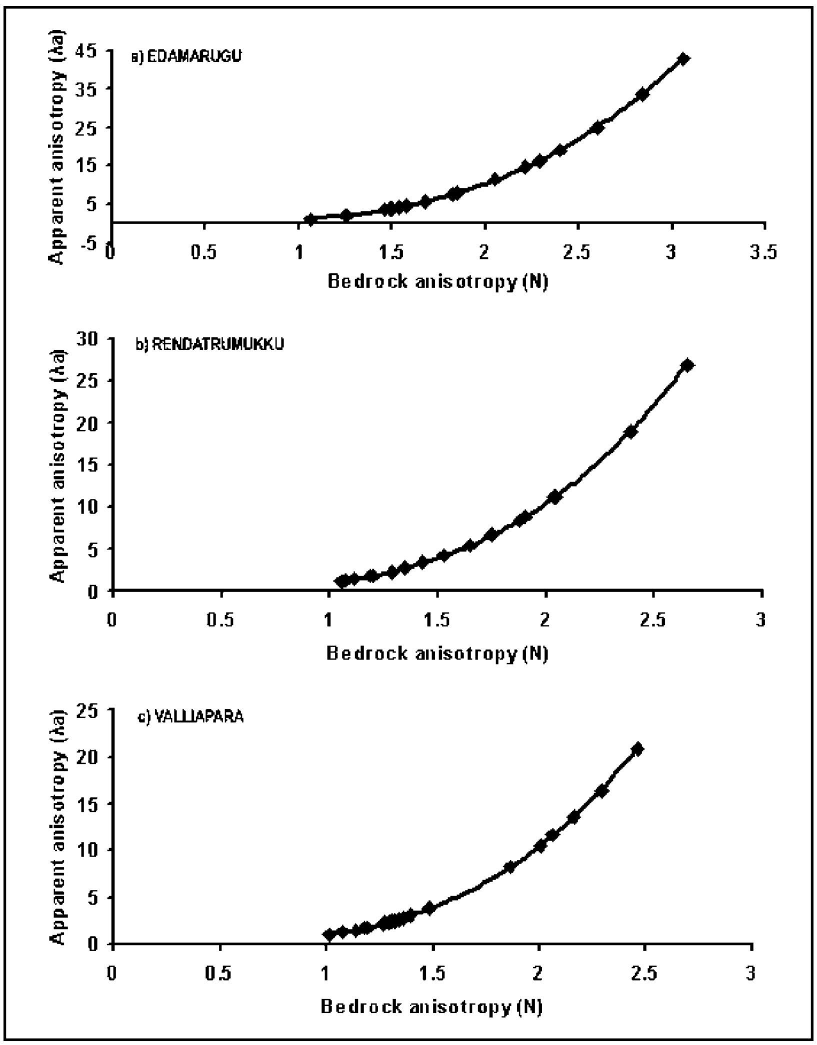

Figure 3. Plots showing upward trends for bedrock anisotropy (N) and apparent anisotropy (la) measured for rocks at Edamarugu, Rendatrumukku and Valliapara.

Azimuthal Polar Plots:

The apparent resistivity values were plotted in the form of Azimuthal polar plots for the three study areas (Fig.4). From these azimuthal plots in the study area two or three fracture directions such as primary, secondary and tertiary along with homogeneous rock mass are identified on the basis of the relative of increasing order of apparent resistivity values. The longest axis of the ellipse in the polar plot indicates maximum resistivity of the rock mass. When the polar diagram conforms to an ellipse, it is taken to represent anisotropy homogeneity (Busby 2000; Senos Matias 2002). The circular pattern of the plot exhibits rock mass without fault/fracture orientation. i.e. the rock is isotropic. The intersection of the fault planes oriented in two directions assumes the cross shape.

From the Azimuthal polar plots the orientation of the fault/ fractures and other geometrical features are identified as a function of depth ranging between 20 and 400 m for the three locations and are shown in below:

Pattern	Depth and Orientation of Geometrical Features at Edamarugu	Depth and Orientation of Geometrical Features at Rendatrumukku	Depth and Orientation of Geometrical Features at Valliapara
Ellipse	40m – E-W 60m – E-W 80m – N-S 140m – N-S 220m – E-W 360m – NE-SW 380m – N-S 400m – N-S	80m – NE-SW 160m – NW-SE 220m – N-S 320m – NW-SE	20m – N-S 60m – NE-SW 120m – NE-SW 240m – NE-SW
Circular	100m	180m	40m, 80m, 100m, 140m 260m, 300m, 320m & 340m
Single fault	20 m – N-S 120 m – N-S 160 m – N-S 180 m – N-S200 m – N-S 280 m – NW-SE 300 m – NW-SE 340 m – E-W	40m – E-W 60m – E-W 120m – N-S 340m – NE-SW 360m – NE-SW 380m – NW-SE 400m – NE-SW	180m – NW-SE 200m – NW-SE 380m – NE-SW
Double fault	240m – N-S; E-W 320m – N-S; E-W	20m – N-S; E-W 140m – N-S; E-W 240m – N-S; E-W 260m – N-S; E-W 300m – N-S; E-W	280m – NE-SW; NW-SE 380m – NE-SW; NW-SE 400m – NE-SW; NW-SE

Majority of the ellipses in the Edamarugu area are oriented in N-S and E-W directions whereas in the Rendatrumukku, they are directed mainly along NW-SE direction. In the Valliapara region the ellipses are oriented on NE-SW direction. More number of circular geometrical features are identified in the Valliapara region than Edamarugu and Rendatrumukku regions. More number of the single faulted system are oriented in N-S, NE-SW and NW-SE in regions areas of Edamarugu, Rendatrumukku and Valliapara respectively. Comparatively the double faulted system (cross shape) were aligned along N-S and E-W directions and were found more in numbers in the areas of Rendatrumukku than the other two regions.

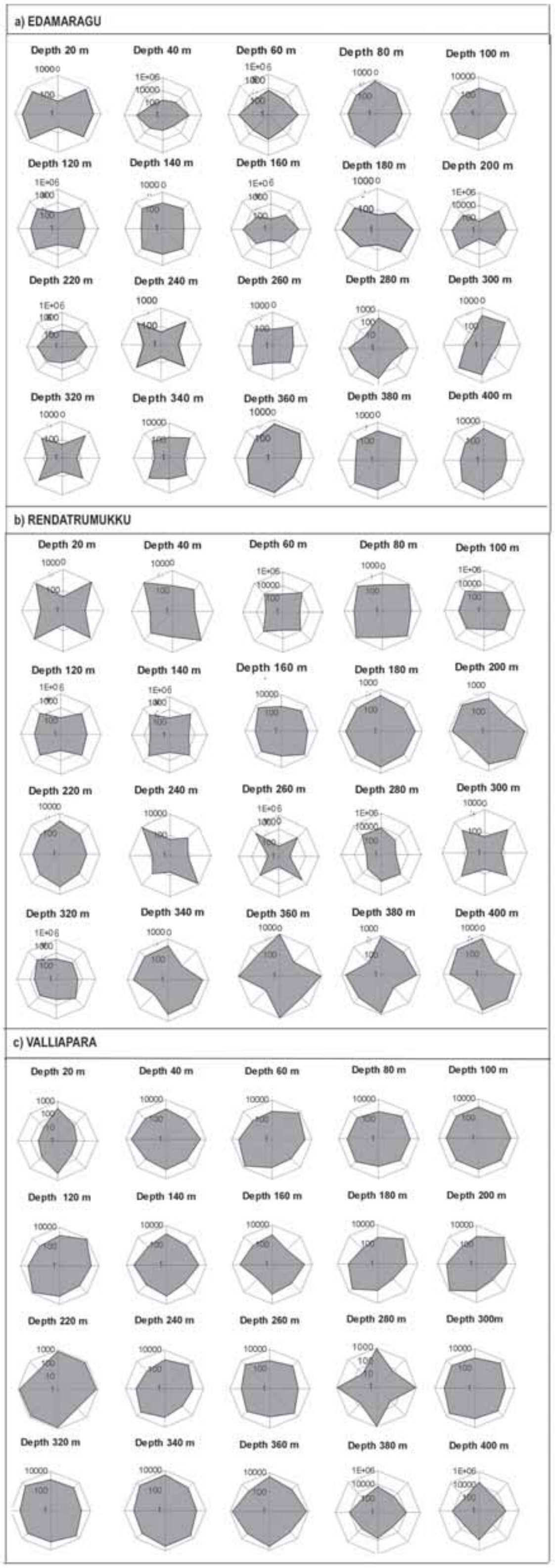

Figure 4. Shows the pattern of Azimuthal apparent resistivity in ohm-m plotted from 20m to 400m depth as tomographic sections at Edamarugu, Rendatrumukku and Valliapara.

Cartesian Azimuthal Graphs:

The Cartesian form of data display is the best visual interpretation. The Azimuthal resistivity data collected at three sites of the study area viz, Edamarugu, Rendatrumukku and Valliapara are converted as percentage of resistance (Fig.5). These data are treated as a function of azimuth in Cartesian coordinates and used to compare the depthwise fracture orientations. Analyses of the data clearly demonstrate the following: The rock mass with less fractures/faults (isotropic) are represented by smooth co-ordinate lines in the Cartesian graphs. The rock dissected with a single fault is prominently represented by trough and peak, whereas, the intersection of fault planes are depicted by uniform amplitudes of peaks and troughs in the Cartesian Azimuthal graphs.

The maximum conductivity zones observed in the Edamargu and Rendatrumukku areas are found along $0^o/180^o$ (N-S) and $45^o/225^o$ (NE-SW) orientations respectively. The intersections of faults/fissures consistently occur in $0^o/180^o$ (N-S), $90^o/270^o$ (E-W) and $45^o/225^o$ (NE-SW) in Edamarugu, Rendatrumukku and Valliapara. The maximum resistances of rock masses are equivalent to the longest axis of the ellipse. The ellipses are represented in the form of prominent peaks are observed along $0^o/180^o$ (N-S) orientation in Edamarugu and $135^o/315^o$ (NW-SE) for Rendatrumukku and $45^o/225^o$ (NE-SW) orientations in the Valliapara region.

Depth Sounding:

In the square array, the depth is equal to 'a' spacing. Plotting of depth versus apparent resistivity values obtained from alpha, alpha', beta, and beta' orientations imply the horizontal conductivity zones (Fig.6). Since, the study area is situated in rocks of igneous origin; the maximum recorded apparent resistivity in this terrain is 54493 Ohm-m and the range of resistivity for the conductivity zone is assumed arbitrarily to be less than 200 Ohm-m. Horizontal fracture/permeability independent of direction and also contribution from vertical or steep fracture sets vary with azimuth creating anisotropic distribution. Consequently, surface Azimuthal resistivity survey cannot detect horizontal anisotropy in macro scale. So the apparent resistivity data collected is plotted against depth or 'a' spacing of the square array to reveal the depthwise variation of apparent resistivity. From these plots, it could be possible to identify the horizontal fracture/ horizontal permeability or hydraulic conductivity. The only difference between the conductivity and resistivity is the way, the data is presented.

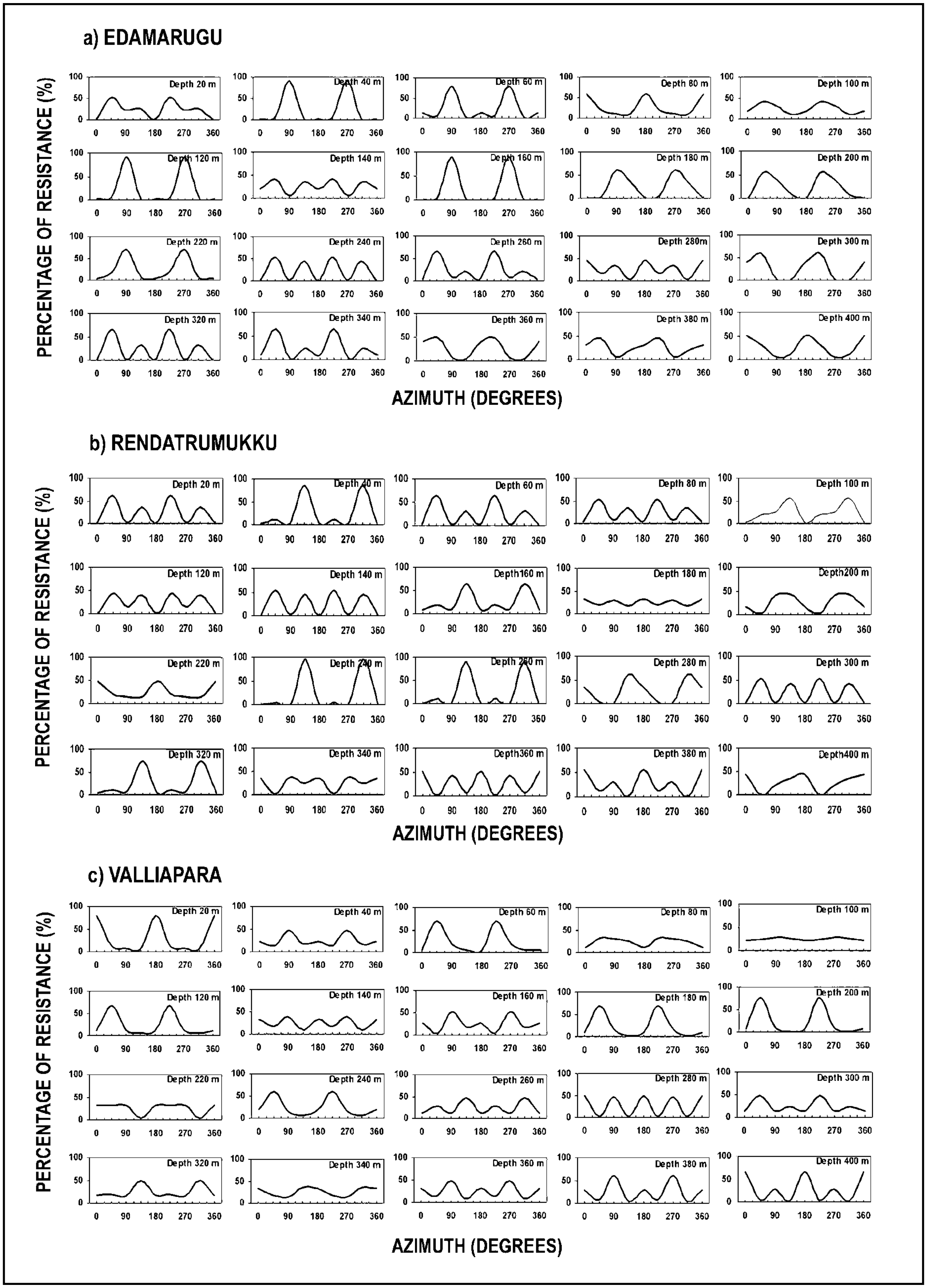

Figure 5. Shows Cartesian Azimuthal graphs for Edamarugu, Rendatrumukku and Valliapara.

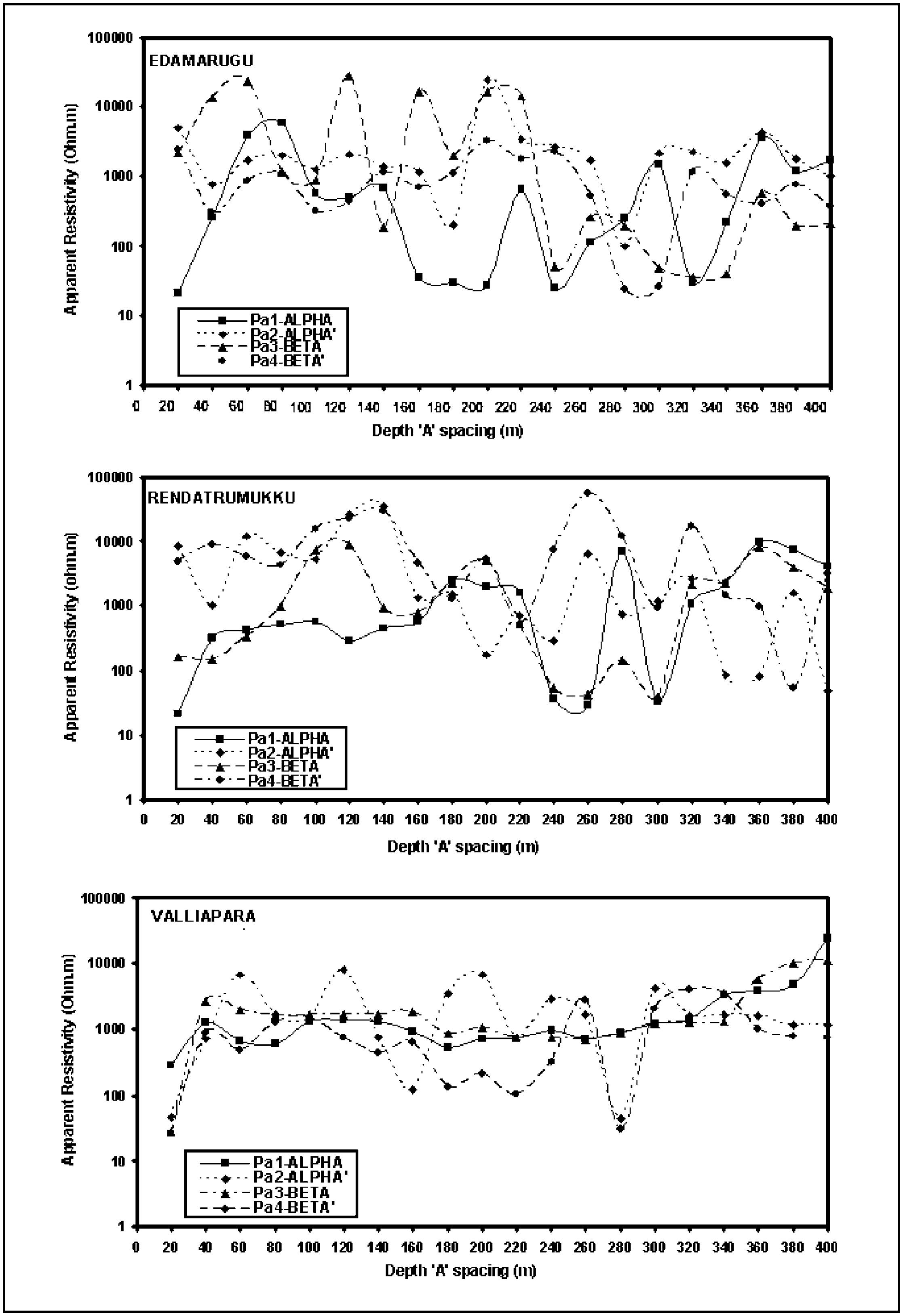

Figure 6. Shows depth wise variation (20-400m) of Azimuthal apparent resistivity values at Edamarugu, Rendatrumukku and Valliapara.

Depthwise identification of low resistivity zones in Ohm-m in different orientations in the study area

Depth in m	0° /180°(N-S)	45° /225°(NE-SW)	90° /270°(E-W)	135° /315°(NW-SE)
20	21[1],22[2],286[3]	47[3]	161[2],27[3]	26[3]
40	—	—	147[2]	—
60	—	—	—	—
80	—	—	—	—
100	—	—	—	—
120	—	—	—	—
140	—	—	180[1]	—
160	34[1]	124[3]	—	
180	29[1]	178[2]	—	133[2]
200	27[1]	—	—	—
220	—	—	—	101[3]
240	25[1],36[2]	—	51[1],51[2]	—
260	111[1],29[2]	—	42[2]	—
280	—	99[1],45[3]	189[1],141[2]	24[1],30[3]
300	33[2]	87[2]	48[1]	26[1]
320	29[1]	—	34[1]	—
340	—	—	40[1]	—
360	—	81[2]	—	—
380	—	—	191[1]	53[2]
400	—	47[2]	—	—

Note: [1] Edamarugu; [2] Rendatrumukku, [3] Valliapara

Data analysis:

The horizontal fractures or permeable zones are identified in the following depths of 20, 40, and 140 to 400 m. But depths of 60 to 120m have revealed no horizontal fractures in the study area. Most of the detected horizontal fractures have N-S (0° /180°) and E-W (90° /270°) orientations than the NE-SW (45° / 225°) and SE-NW (135° /315°) orientations. Of the three locations, more number of horizontal fractures is identified at Edamarugu followed by Rendatrumukku. The least number of horizontal fractures is found in Valliapara region.

DISCUSSION AND CONCLUSIONS

Based upon the relative resistivity distribution patterns in the Azimuthal Polar Plots and Cartesian Azimuthal Graphs, the orientations of the primary, secondary and tertiary features are discussed. Majority of the primary fractures oriented in NW-SE in Edamarugu and N-S and NE-SW directions in Rendatrumukku and Valliapara are clearly depicted by low resistivity distribution patterns in the Azimuthal Polar Plots and Cartesian Graphs. Bulk of secondary fractures trending E-W and NE-SW are represented by relatively high resistive values than the primary fractures. Similarly the tertiary fractures in Edamarugu, Rendatrumukku and Valliapara are confined to NE-SW, NW-SE directions and represented by comparatively higher resistivity values than the primary and secondary conductivity zones.

The high resistive rocks in Edamarugu are equally distributed in all orientations except NW-SE directions, whereas in Rendatrumukku, the high resistive rocks are found along NW-SE and E-W trends but the trends are different in Valliapara. The high resistive rock distributions are clearly seen along the elongated axis in the Azimuthal polar plots and high peaks in the Cartesian Azimuthal graphs. The horizontal fracture / permeable zone at various depths in the study area are represented in the form of Cross in the Azimuthal polar plots and high peak with trough in the Cartesian Azimuthal Graphs. The circular pattern in the Azimuthal polar plots and smooth coordinated lines by Cartesian Azimuthal graphs represent resistive and / or more or less equal resistive rocks.

The delineation of low resistivity zones at depths in the study area as horizontal permeable zones comply with published reports that elastic deformation due to earthquake creates low resistivity and are summarized here. Geoelectric potential difference (electric field) changes possibly associated with of earthquake occurrences in the other parts of the world were reported (Corwin & Morrison 1977; Varotsos & Aledzopoulops 1984a, 1984b; Nagao et al. 1996, Mogi et al. 2000). The changes of electric field accompanying seismic waves have long been known as *electro seismic effect* (Thompson 1939; Martner & Sparks 1959). The ground induced elastic deformation associated with earthquake cycles and development of cracks due to excess rock volume pressure decrease the resistivity (Thompson 1939; Long & Rivers 1975; Brace and Orange, 1968). Hydraulic conductivity along the vertical and horizontal fractures or permeable zones also affects the electrical resistivity (Abu Hassanein et al. 1996). The identification of the low resistivity zones is key point to detect the fault/fracture trends. These conductive faults/permeable zones in the study area found to have very low resistivity than the basement rock. Similar identifications of conductive zones associated with fault structures were also reported in other parts of the world by Electromagnetic Research Group of Active Fault (1982), Subrahamanyam and Bhalla (1997) and Fuji-ta & Ikuta (2000). The repeated tremors in vicinity of the study area might have generated pulverized cataclastic deposits in the fault zones.

Year	Place	Latitude-Longitude	Magnitude
2000	Erattupetta	9°70′ N – 76°73′ E	
12 Dec 2000	Pala	9°68′ N – 76°80′ E	5.0
2001	Erattupetta	9°70′ N – 76°80′ E	4.8
07 Jan 2001	Pala	9°70′ N – 76°73′ E	4.8
22 May 2001	Pala	9°70′ N – 76°73′ E	3.6
15 Nov 2003	Erattupetta	9°70′ N – 76°80′ E	3.0

The presence of cataclastic in the fault zone may be another cause for the development of low resistivity zones. (Scholz et al 1993). The compressive or frictional force in the fault has induced the thermal effects and alteration. The increase of clay content due to pulverization of cataclastic would increase the thermal efficiency for a long duration. The continuation of the thermal effects would have increased the high conductivity nature of the fault/ fracture or decrease of electrical resistivity in the fault zone (Fuji-ta & Ikuta 2000). The accurate mapping of the complex fault /fracture system by square array resistivity have delineated the zones of the recent seismic events with epicenter zones which had already produced six minor tremors since 2000-2003.

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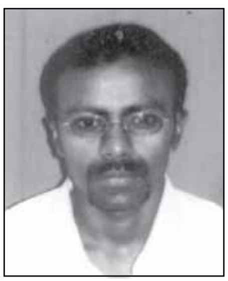

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