istemoids was from a group of cells (multicellular) (Figure 13). The proembryogenic nodules were found to be present towards the periphery of the calli, the rest of the cells in the calli probably acting as nurse tissue to the emerging embryoids. These observations are in confirmation with those made by Schwendiman *et al.*[9].

Continued meristematic activity was observed in the calli which led to the formation of a central zone of the embryonic shoot apex (Figure 14). Subsequently, the apex became well defined as a rounded dome (Figures 15–17). After 6 weeks of culture in the regeneration medium, green-coloured structures were observed on the surface of the calli. All these structures were highly vascularized and they play the role normally attributed to the haustorium by taking up nutrients from the culture medium. Cross sections of these structures showed a large number (10–25) of meristemoids and shoot primordia (Figure 12). A representative series of developmental stages is shown in Figures 14–20.

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Differentiating conductive and resistive inhomogeneities: A new approach in groundwater exploration

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Lateral inhomogeneities, such as dykes or shear zones give rise to false low-resistivity layers in vertical electrical sounding curves which are likely to be misinterpreted as a water-bearing zone at depth. In groundwater exploration it is necessary that such anomalies be identified, i.e. a near-horizontal discontinuity, a conductive (probably water-bearing) lateral inhomogeneity or a resistive (e.g. a dyke) vertical feature. Lateral effects can be distinguished from those due to depth effects by offset soundings or crossed azimuth soundings, while conductive lateral inhomogeneities can be differentiated from resistive ones by a modified azimuthal sounding technique. Under favourable geoelectric conditions it may be possible to determine the direction and amount of dip of the vertical feature as well so that well sites could be located at a suitable distance in the down dip direction of the feature.

IN the predominantly crystalline rock terrains of south India, groundwater occurs in two distinct zones, namely the near-surface weathered and decomposed rock material (regolith) and the joints and fractures that may extend to a few hundred metres depth in the underlying bed rock. Shear zones are also often found to contain substantial amounts of groundwater, as such zones are generally highly fractured and jointed, a condition conducive for storage and movement of groundwater. Overexploitation of groundwater in several parts of southern India has resulted in the drying up of the weathered rock horizon, restricting the availability of groundwater to the fractured rock zones, which extend to relatively deeper levels. The success of a borewell under these conditions depends on the presence of such deep water-bearing zones, and therefore, it is essential that they be identified to successfully locate sites for constructing water wells.

Availability of groundwater in these fractures, joints, shear zones, etc. is facilitated by weathering of the parent rock along them, increasing their porosity, and hence, water holding and transmitting capacity. It must be emphasized here that below a certain depth the weathering of the parent rock is confined mainly to the joint planes of the fracture and shear zones, leaving the bulk of the rock body un-altered and relatively fresh. The weathering renders such zones electrically more conductive in comparison to the country rock, and hence, at first glance, it may appear to be an easy target for exploration through geo-electric techniques. However, these weak zones in the country rock, often having narrow widths and with dips ranging from vertical to near-horizontal, are likely to be missed during investigations. But, in view of the importance of identifying them for a successful groundwater development programme, detailed investigations were carried out to develop a suitable exploration technique. From these studies, a field methodology has been evolved to identify vertical and near-vertical features, differentiate them as geo-electrically conductive or resistive and then approximately determine the direction and dip amount of these lateral inhomogeneities.

The vertical and near-vertical joint/fracture zones, narrow shear zones, dykes and veins can essentially be considered as lateral inhomogeneities in the country rock. Their presence in an area may be recognized by the resistivity anomalies they generate, provided that these inhomogeneities are sufficiently wide, and also that adequate resistivity contrast exists between them and the country rock. Resistivity profiling using alpha-, beta- and gamma Wenner arrays[1,2] or vertical electrical soundings (VES) such as Barker's[3] offset Wenner soundings and crossed azimuth soundings[4] are helpful in identifying lateral inhomogeneities. However, these techniques are used only when one is specifically looking for the presence of lateral inhomogeneities and rarely otherwise. In groundwater exploration using resistivity methods, the normal practice is to carry out a few vertical soundings in the area of interest and select the best out of them for constructing wells. The problem is therefore to identify the presence of vertical features, if and when present, from an analysis of these VES curves without resorting to the above additional techniques. It is known that a lateral inhomogeneity, be it resistive or conductive, gives rise to a false low-resistivity geo-electric layer in the VES curve, when one of the current electrodes is in contact with it[4,5]. A low-resistivity layer in a VES curve may also be caused by a relatively more conductive lithological unit at depth. The problem is shown in Figure 1, wherein three instances of diverse geological conditions giving rise to essentially identical VES curves are shown. This underlines the need for a technique to differentiate between the causes of these anomalies.

The objective of identifying a lateral inhomogeneity is achieved by the so-called offset sounding method described by Ballukraya *et al.*[4], wherein a series of closely spaced soundings are carried out along a common electrode spread direction. Schlumberger electrode array has been found to be preferable for this purpose as it minimizes errors in the measured values that may be introduced by the shifting of potential electrodes for each and every measurement, as with Wenner electrode

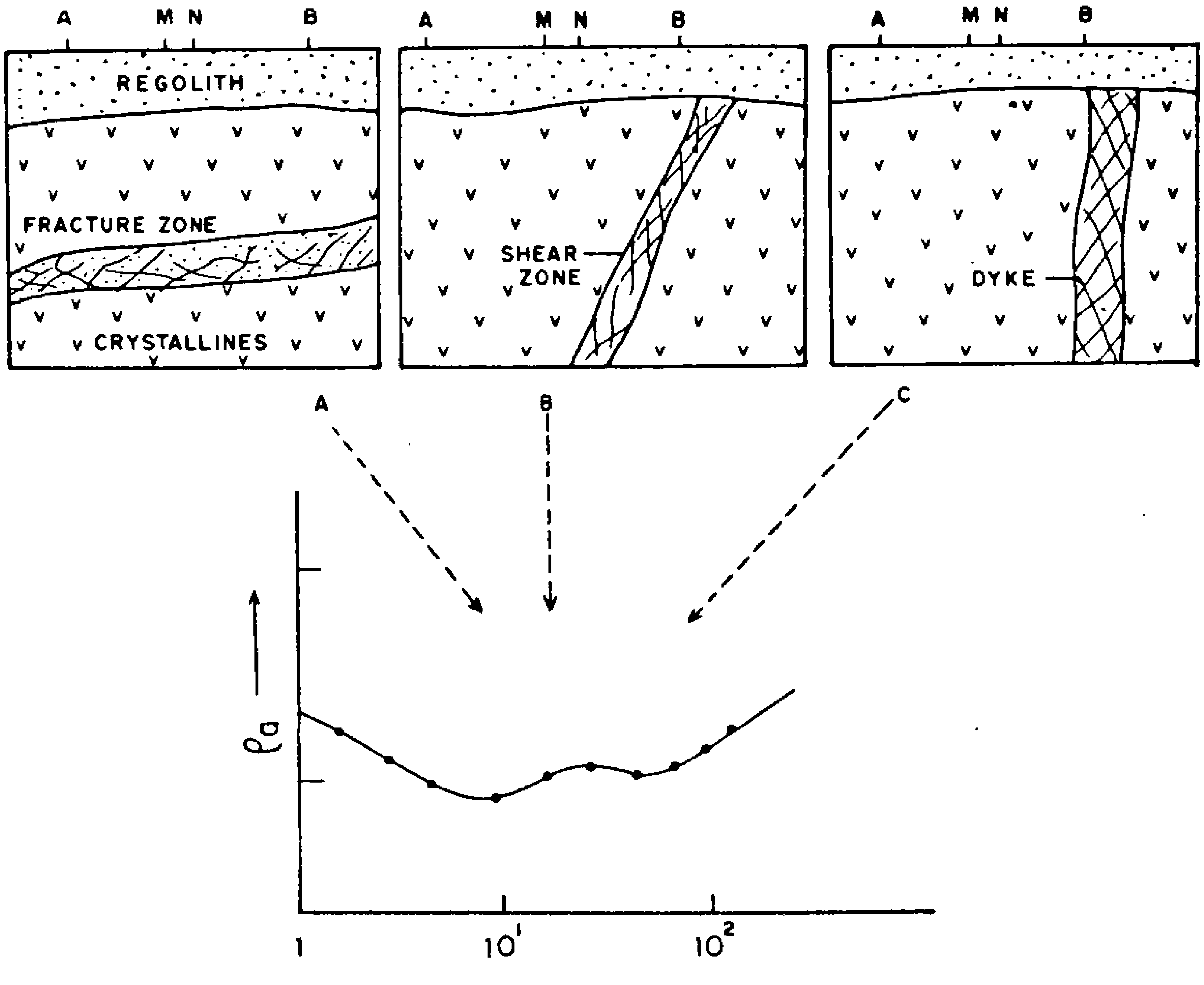

Figure 1. Shape of the VES curves that may be obtained over three different geological sections.

configuration. The presence of a lateral inhomogeneity will be generally reflected in the form of a false low-resistivity layer in the ascending part of the VES curve. Once such an anomaly is noticed, two or more soundings are carried out, close to each other, along the same electrode spread azimuth at distances of about 10 to 15 m from each other. If the low-resistivity layer noticed in the VES curve is caused by a horizontal discontinuity (Figure 1 *a*) at some depth, the current electrode separation (AB) at which the curve starts its downward trend will essentially be the same in two or more of the offset VES curves. On the other hand, if it is due to a lateral inhomogeneity (Figure 1 *b* and *c*), the electrode separations at which the low-resistivity layer begins will be offset by the respective distances between the sounding stations. The AB separation at which the low-resistivity layer occurs in these VES curves will thus clearly indicate its cause (lateral or horizontal) and its location (distance or depth).

Figure 2 shows a set of four VES curves obtained

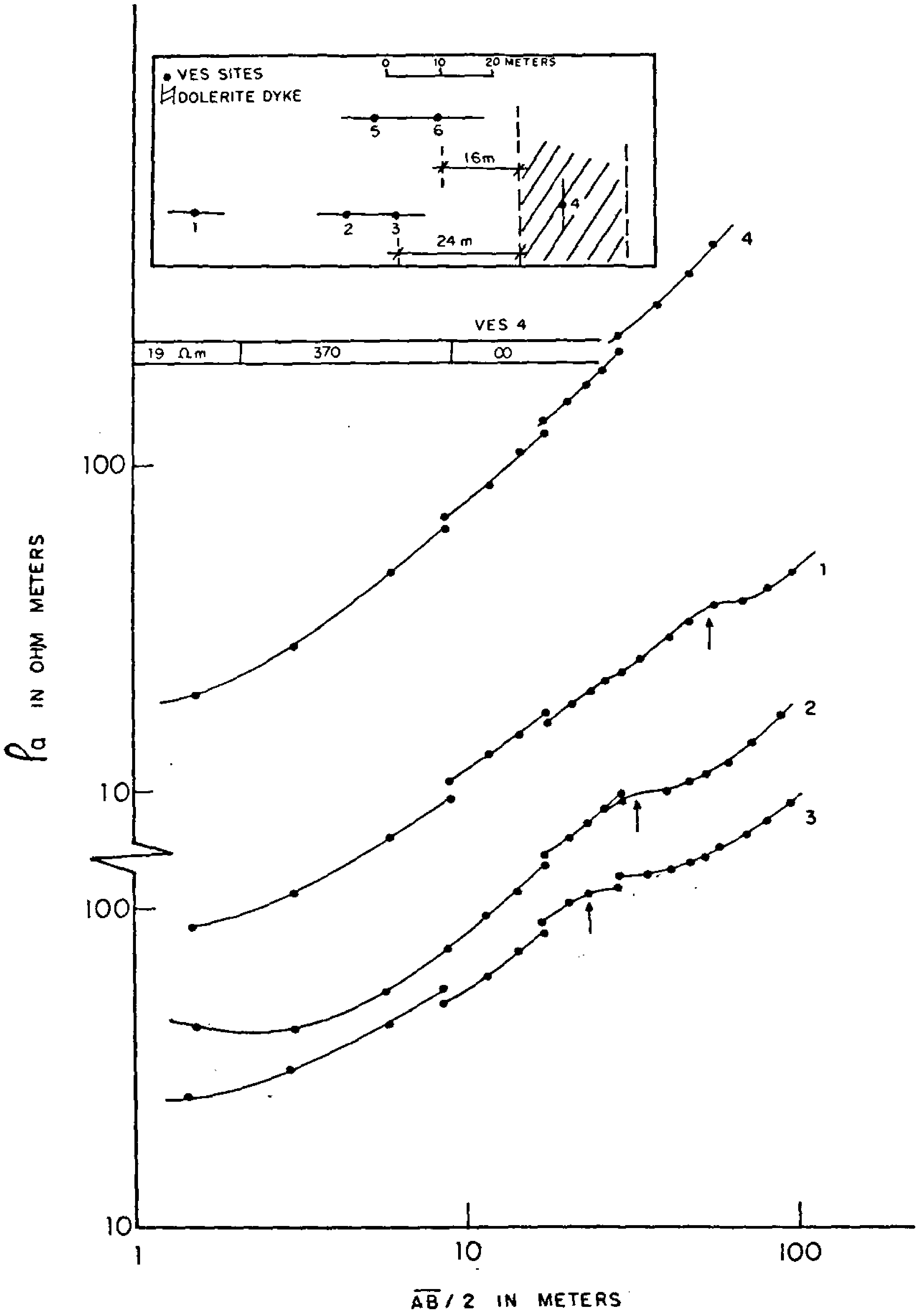

Figure 2. Effect of a resistive lateral inhomogeneity on VES curves.

near a dolerite dyke in Veerapuram village, Tamil Nadu (12°44′30″N, 80°0′05″E). This 20 m wide dyke is found exposed for over one km length. Three soundings are to the west of the dyke, with electrode spread direction normal to the strike of the dyke. As seen from the VES curves, a low-resistivity layer is generated whenever one of the current electrodes crosses the dyke. The AB/2 separation at which the anomaly begins is equal to the distance between the VES site and the dyke–country rock contact. As observed from the figure, the low-resistivity layers begin at AB/2 = 63, 33 and 24 m respectively in VES curves – 1, 2 and 3, thus offset by the inter-VES station distances (9 and 30 m). This clearly illustrates the effect of a resistive lateral inhomogeneity on the shape of VES curves and the generation of a low-resistivity layer therein.

Once the presence of a lateral inhomogeneity is thus established, its strike direction can be found out by carrying out two or more sets of offset soundings along azimuths parallel to that of the first set, and joining the inferred contact zones (inset, Figure 3).

A lateral inhomogeneity thus identified can be any one of the features such as joint/fracture zone, dyke, vein, fault or shear zone. In geo-electric terms, it can

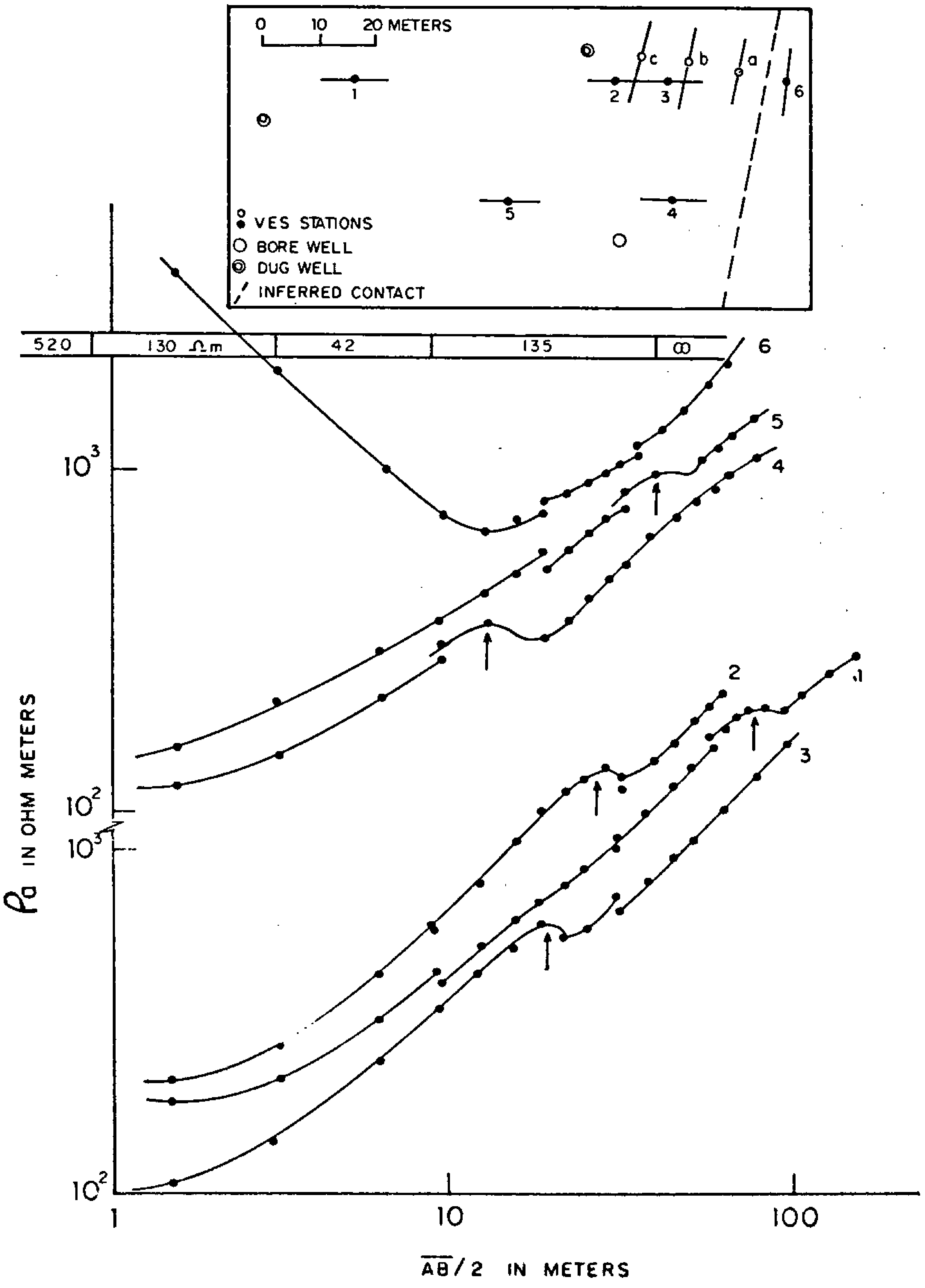

Figure 3. VES curves from Athur study area with an inferred conductive lateral inhomogeneity.

be a resistive or a conductive layer in relation to the host rock. Both give rise to a false low-resistivity layer and differentiating the two in the field, on the basis of geoelectric parameters alone is generally difficult if not impossible. In groundwater exploration, however, it is essential that we establish the true nature of the inhomogeneity. For, a conductive zone may be water-bearing, hence the target of exploration, while a resistive body could be a massive dyke, to be avoided while locating well sites. The problem is solved by carrying out another set of soundings, but this time over the inferred inhomogeneity and with the electrode array parallel to the strike direction of the inhomogeneity. These VES curves, obtained at stations located directly over the inhomogeneity, are likely to indicate the nature of the body, by the presence or absence of geo-electric layers corresponding to relatively thick, decomposed or weathered rock zones. A resistive body (say, a massive dyke) will normally have a very thin weathered rock layer, whereas a conductive body (say, a water-bearing fracture or shear zone) will have a comparatively thicker weathered rock layer at the top. Thus, VES curve-4 in Figure 2 shows a three-layer section with very thin weathered rock layer as expected over a dolerite dyke. VES curve-6 in Figure 3 on the other hand, shows a five-layer section, with substantially thick overburden as well as weathered and partly weathered rock horizons, indicating that underlying it is a comparatively conductive zone. This is helpful in differentiating a resistive from conductive lateral inhomogeneity.

It is possible that the lateral inhomogeneity is inclined in which case the direction and amount of the dip have to be estimated to locate the well site at a suitable distance away from the surface trace of the inhomogeneity. The ground distance to a favourable location in the down dip direction will depend on the dynamic water levels prevailing in the area – deeper the levels, larger the distance to the prospective well site for a given dip.

An empirical method of estimating the dip of the

Table 1. Interpreted results of VES curves from Athur area

VES no.	Layer resistivity (Ωm)					Layer thickness (m)			
	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4
1	170	1020	Very high			2.1	15.8		
2	200	1800	Very high			2.1	9.5		
3*	100	3500	?			1.8	?		
4*	105	420	2500 (?)			1.9	6.3	?	
5*	190	570	3870	?		1.5	7.2	?	
6	520	130	42	135	High	0.9	2.1	5.6	32.8

*Values approximate/interpretation incomplete.

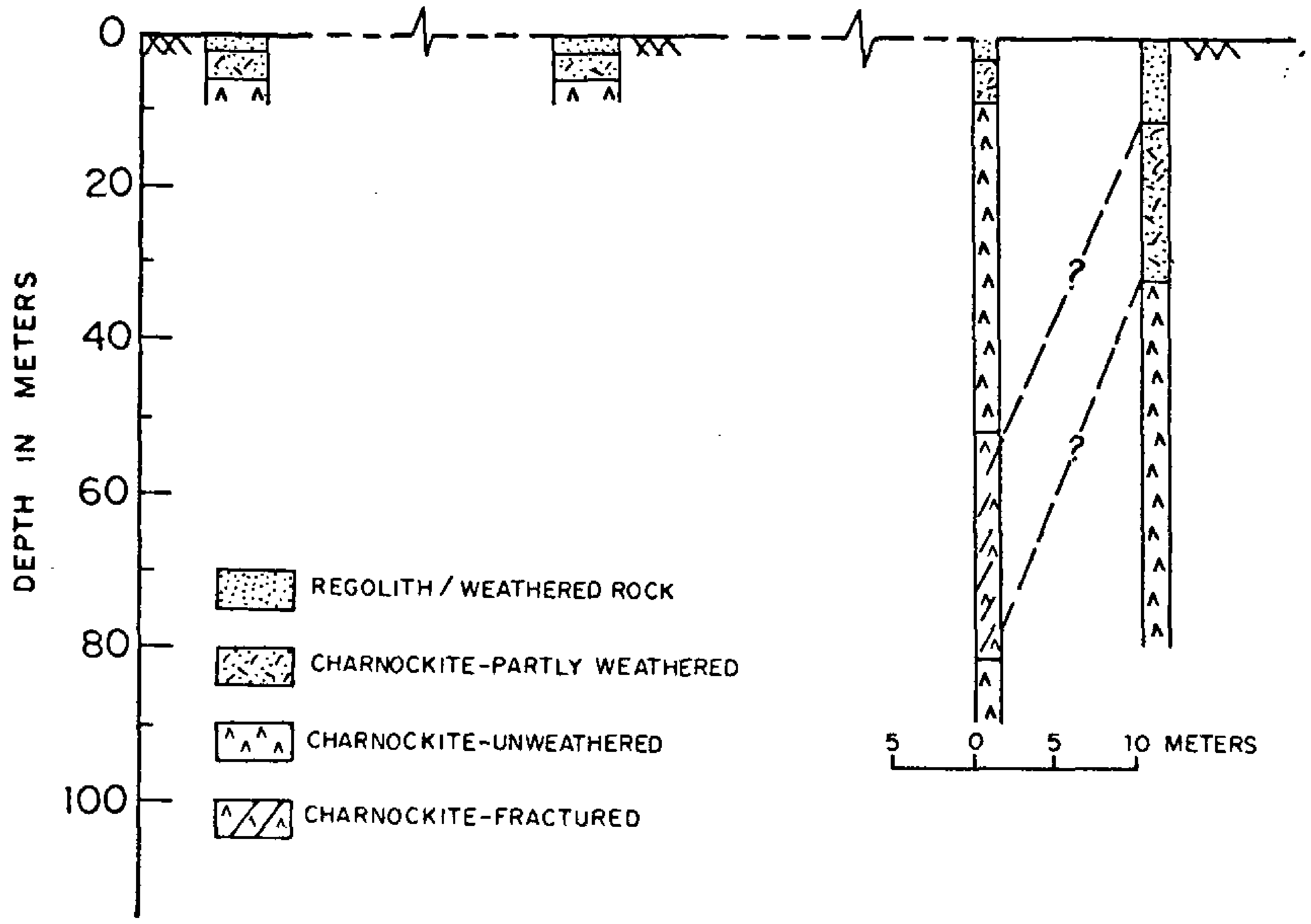

Figure 4. Subsurface geology of the Athur study area showing steeply dipping fracture/shear zone.

vertical feature is by conducting a series of soundings, in a direction normal to the strike of the inhomogeneity and with the electrode array parallel to the strike direction (Figure 3 *a,b,c*). A conductive zone dipping in the direction of these soundings is likely to give rise to a low-resistivity anomaly in the VES curves, and from the depths at which they are indicated in two or more VES curves, the approximate amount of dip can be estimated. Though dipping bodies can be recognized by theoretical analyses of resistivity data[6], the methods are not unambiguous nor can they be easily adopted in field. Therefore, the empirical method suggested above is far more advantageous.

The proposed technique was tested in the field near Athur town (11°34′40″N, 78°35′14″E) in Tamil Nadu. The area is underlain by charnockite rock with a thin regolith and weathered rock zone near the surface. Several vertical electrical soundings were carried out in a grid pattern using Schlumberger electrode array, in a small plot of land for the purpose of locating a site for the construction of an agricultural borewell. Six of the VES curves obtained from this are shown in Figure 3, along with their relative locations in the inset. The presence of a lateral inhomogeneity is indicated by the false low-resistivity layers in the offset VES curves 1, 2 and 3 and confirmed in VES curves 4 and 5 from a second profile. From the position of the anomalous low-resistivity geo-electric layers in each of the VES curves, the contact of the inhomogeneity was fixed at distances of 75, 27 and 18 m respectively to the east of stations 1, 2 and 3 along the first profile and 12 m from station 4 along the second profile. The approximate strike of the inhomogeneity was established by connecting the contacts along the two profiles (inset of Figure 3). In the next step, VES-6 was carried out over the inferred inhomogeneity with the electrode spread direction parallel to the strike of the anomalous body. The results of the analysis of these six VES curves, using Auxiliary Point Charts[7] and refined by computer simulation are given in Table 1. The quantitative interpretation is partial and approximate in the case of VES curves influenced by the effects of the lateral inhomogeneity. A marked difference is observed in the geoelectric sections indicated by curves 1 to 5 and that of curve 6. While a thick overburden ($h_1 + h_2 + h_3 = 8.6$ m) and a comparatively thick partly weathered rock layer ($h_4 = 32$ m; $\rho_4 = 135\ \Omega$m) is indicated from VES-6, the depths to bed rock layer at stations 1 to 5 are much smaller, less than 2 m on an average. This sharp contrast indicates the existence of a conductive lateral inhomogeneity in the area of VES-6 which could be interpreted as a water-bearing shear/fracture zone.

The sub-surface lithology as observed from the dug well sections in the area (Figure 4) confirms the geological interpretation of geoelectric data in respect of VES stations 1 to 5. Two borewells were drilled, one at station-6 and the second at a distance of 12 m, from station-6, towards station-3. The location of the second well was on a trial basis. The lithological sections of the two borewells are shown in Figure 4 and the drilling of the second well provided useful information.

Both borewells yielded substantial quantities of groundwater, 95 lpm (litres per minute) at VES-6 and 140 lpm from the second well. Of greater interest, however, is the lithological section thrown up by the two borewells. At VES-6 a thick over burden (10 m) is present underlain by a 24 m thick partly weathered rock zone, followed by the bed rock. In the second well, fresh bed rock was encountered at a relatively shallow depth of 9 m. In addition, a fractured rock horizon extending from 49 m to 78 m depth was also encountered in this second borewell. Much of the groundwater in case of the first well is from the weathered rock zone between 25 and 34 m, while in the second well it is mainly from the fractured rock zone, extending between 49 and 78 m depth. It has been reported that in the summer months, following the commissioning of the wells, the discharge from the first borewell reduces sharply while that from the second well sustains to a large extent. The drill cuttings obtained from the fractured rock zone in the second borewell showed distinctive polished surfaces as well as microscopic fractures, indicating that it may be a shear zone, steeply dipping from the area of VES-6 towards VES-3. The interpretation of the geoelectric data as to the presence of a conductive lateral inhomogeneity has been thus proved correct. The higher yield and its sustained nature, in the second borewell are due to the shear zone being at a deeper level, and thus remaining fully saturated even in summer compared to the near-surface aquifer zone in borewell-1. This also underscores the need for determining the dip of the lateral inhomogeneity to locate the well site at an optimum distance from the surface contact.

The methodology suggested in this paper for identifying water-bearing zones in areas underlain by crystalline rock formations is a simple, field-friendly yet effective technique, which can be applied in groundwater investigations quite successfully.

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