Comparison of surface and sub-surface geophysical investigations in delineating fracture zones

N. S. Krishnamurthy*, Dewashish Kumar, V. Ananda Rao, S. C. Jain and Shakeel Ahmed

Indo-French Centre for Groundwater Research, National Geophysical Research Institute, Hyderabad 500 007, India

In present days because of overexploitation of aquifers, saturated zone is mostly limited to fractured portions in granitic areas. Delineation and distribution of such fractures is important to exploit and simulate groundwater. Delineation of thick fracture zones is possible by surface geophysical methods such as resistivity technique. However, in the case of thin fracture zones, their effect is masked and an integrated approach needs to be followed for identifying these zones. Geophysical studies were carried out in Maheshwaram watershed, Andhra Pradesh, India including well logging in some of the borewells. In some cases, the results of surface SP and resistivity sounding have considerable correlation with geophysical logs. The thin fractures could be identified with resistivity and gamma logs. The surface SP studies show potential anomalies indicating the presence and continuation of fractures.

FRACTURE zones in hard rock terrane play an important and critical role in fluid flow within the sub-surface, such as the movement and accumulation of groundwater as well as transport of contaminants. Many a time the minor fractures present in the bedrock, if well-connected, can give copious supply of groundwater. In potential bedrock aquifers, individual boreholes must be targeted to intercept fracture zone or even a fracture that could be from 5–10 ft to less than 1 ft wide. The water resource professionals need additional, site-specific information to precisely locate boreholes to intercept specific bedrock-fracture zones. Delineation of fracture zones in such low permeability rocks is thus a challenging task. Of all the geophysical methods, resistivity method is the most suitable method for investigations of fracture aquifers because localization of fracture zones is based on the fact that they exhibit lower resistivity compared with the undisturbed rocks[1]. But in most of the cases, the resistivity technique, particularly sounding, alone cannot identify the fractured aquifer, because the layer gets masked on a sounding curve as its thickness becomes less compared to its depth of occurrence. Hence, an additional technique along with the resistivity technique will help in identifying such zones. The use of geophysical techniques are well-documented for groundwater investigations[2,3]. Several workers used various geophysical methods to study high yielding crystalline bedrock aquifers[4–6].

Among the additional techniques that support VES interpretation, self-potential (SP) method is one. Though SP surveys are mainly used for mineral exploration, these are also being used for knowing the movement of water or the delineation of potential fracture zones[7,8]. In a porous or fractured media, the relative movement between solid matrix and electrolyte (groundwater) causes an electrical potential at the interface. If the water movement was brought by a hydraulic gradient, a difference of electric potential called streaming potential/self potential (SP) would result between any two points in the direction of motion[9,10]. The presence of a pressure gradient in the sub-surface, however, is not a sufficient condition to ensure the existence of an electric potential on the surface. As defined by Fitcherman[11], it is necessary to have a pressure gradient parallel to a boundary that separates regions of different streaming potential coefficients. In such cases, an electric field equivalent to that by a surface distribution of current dipole along the boundary is developed. Borehole wall imaging is currently the most reliable means of mapping discontinuities within boreholes. Several types of discontinuities that have been identified in borehole logging are bedding, cleavage, veins, joints, fractures and faults. As these imaging techniques are expensive and thus not always included in a logging run, a method of predicting fracture frequency directly from traditional logging tool response would be very useful and cost effective. The resistivity value will decrease where fractures are present. However, these trends can be difficult to see on a single plot of log response, but a cumulative sum plot of the various logs provides a clearer picture of anomalous zones in the borehole[12,13].

In order to ascertain the presence of these fractures and to study the response of electrical self-potential method in delineating these fracture zones sub-surface, well logging and surface electrical self-potential investigations were carried out at some of the wells. The present paper analyses in detail the results of SP and VES interpretation in the presence of geophysical well logging and lithologs. Thus the actual fracture zones encountered are correlated with the output of the SP and VES.

The Maheswaram watershed having an area of 60 km^2 lies between geographical longitude 78°24′30″E and 78°29′00″E and between latitudes 17°06′20″N and 17°11′00″N and forms part of toposheet 56 K/8. Subtropical climatic conditions are prevailing in the area with a minimum and maximum temperature of 22°C and 44°C respectively. It receives more than 80% of its rainfall from SW monsoon. The average rainfall in the area is 573 mm. The area exhibits undulating topography with subdendritic type of drainage. The area is marked by a number of gullies that drain into local streamlets with eroded banks. The location of the study area and geological features incorporating the drainage pattern are shown in Figure 1. A thin film of soil covers the area; sandy loam on the elevations and clayey soil in the lower

*For correspondence. (e-mail: nskrishnamurthy@sify.com)

reaches. The rate of infiltration is moderate to high in sandy loam compared to the clayey soil. The area is underlain by granites of Archaean age, pink and grey in colour and medium to coarse grained in texture. They have undergone variable degree of weathering and emplacement with depths extending even up to 15 m followed by fracturing at many places[14]. The country rock is intruded by dolerite dykes in the northern part of the basin. The dyke located in the extreme northern part strikes east–west with about 15 m width (Figure 1). Another dyke exposed about 1 km south of the first one, strikes N60°E–S60°W with a width of about 20 m at places. A quartz vein of about 20 m width with a strike of ENE–WSW is exposed in the drainage divide in the southern boundary of the watershed. A few quartz intercalations are observed parallel to the dolerite dykes and in the borewell sections between 20 m and 45 m bgl. Groundwater in the area occurs under water table conditions in the weathered granite and in semi-confined conditions in the fractured granites. The depth to water level varies from 11 to 20 m. The yield of the borewells range from 1000 gph to 5000 gph. The high yielding borewells are either recharged by the irrigation tanks or tapping the deeper fractures.

Figure 1. Drainage map of Maheswaram watershed.

About 85 vertical electrical soundings (VES)[15] were carried out in the study area using Schlumberger configuration to arrive at resistivities and thicknesses of different sub-surface zones. The electrode spread is increased such that the influence of the bedrock is obtained with a sufficient number of observations on the last ascending slope of the sounding curve. In order to obtain direct information on the sub-surface lithology particularly about the fractures, a few borewells have been drilled in the area based on the hydrogeological and resistivity investigations. From the lithologs of the borewells collected while drilling, it was found that fractures were intercepted in a number of wells and the yield of the wells was increased in general. In addition, SP investigations were made at selected sites[16]. SP measurements were carried out at four sites in a grid pattern with traverse interval of 4 m and station interval of 4 m to analyse the iso-potential lines for identifying the fracture zones in correlation with other results. Geophysical well logging was carried out in a few boreholes using different sounds such as SP, temperature, point resistance (PR), short normal (SN), long normal (LN) and gamma logs[17].

Normally the thin fractures, which are separated and sparsely distributed within the compact rock below a weathered zone cannot be delineated by a resistivity sounding but most of the times, it will be identified by a thick single layer with reduced resistivity. A combined analysis of the resistivity sounding results, well logging and the lithologs at Maheswaram watershed has been made at a number of sites and two such cases are discussed below, where a thick fracture zone has occurred at one place and two thin fracture zones at close interval have been encountered at another place.

Comparison of sounding results with that of well logging at well no. IFP-1 is shown in Figure 2 along with the litholog. The geological sequence encountered while

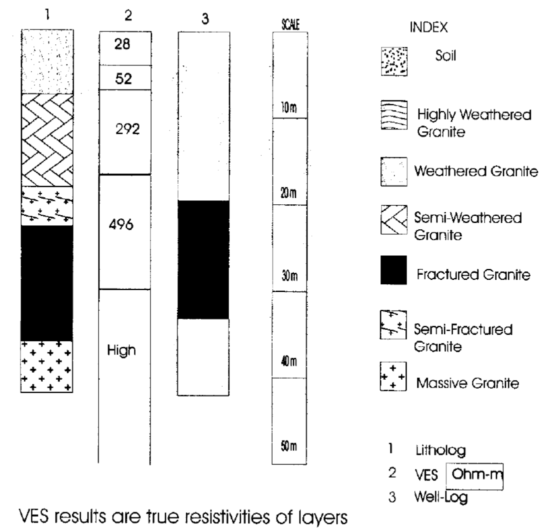

Figure 2. Comparison of VES, litholog and well log results for well no. IFP-1.

drilling is the top weathered and semi-weathered layer followed by fractured granite underlain by compact granite at a depth of about 36 m. The resistivity sounding results show a resistivity of 292 Ω-m for the semi-weathered zone followed by fractured granite from 16 to 30 m with a resistivity of 496 Ω-m, underlain by bedrock. Though this appears to be a single layer in the sounding curve, in fact the layer may contain some thin fractures within the hard rock and partly saturated. Hence, the resistivity of this layer is in between that of the top semi-fractured and bottom bedrock. The SP and temperature logs (Figure 3) do not indicate any anomalous zone. The SN and LN logs (Figure 3) show low resistivity around 31 m and the PR log indicates a low resistance around 32 m. The apparent resistivities as observed against weathered zone are 110 Ω-m and 600 Ω-m by SN and LN respectively whereas against fractured zone are 220 Ω-m and 1200 Ω-m by SN and LN respectively. The details of the depths of the fractured zone observed by different logs are given in Table 1. The gamma log (Figure 4) indicates high activity below 22.5 m onwards which is in the range of 500 counts per second (cps) compared to that above 22.5 m which is in the range of 300 cps or less. This high activity can be attributed to fractured zone. Combining all these we can see that there is a clear-cut fracture zone around 25 m as shown in Figure 2. The anomalies found in the surface SP profiles (Figure 5) also indicate the presence of water-filled fractures and also their extension along N–S direction. The surface SP technique does not have the depth control, but the anomalies indicate the presence/extension of saturated fractures.

The borewell no. IFP-9 was drilled up to a depth of 42 m and the yield is 150 lpm. The fracture zones as observed from litholog are encountered at a depth of around 20 and 30 m. The SP, temperature and resistivity logs are shown in Figure 6. SP and temperature logs do not indicate any anomalies. The LN and SN indicate low resistivity zones around 30 m which could be saturated fracture zones. The apparent resistivity as seen from logs against weathered zone are 50 Ω-m from SN log and 250 Ω-m from LN log, whereas against fractured zone are 100 Ω-m from SN and 400 Ω-m from LN logs. The gamma log shows high activity around 20 and 31 m (Figure 7). The depths of these fractures as observed in logs are given in Table 1. The indication of these fractures from well logs and the litholog are shown in Figure 8 along with results of resistivity sounding. These sounding results show a resistivity of 92 Ω-m for fracture zone. The surface SP

Table 1. Depths of the fracture zones inferred from various logs

Well no.	Log name	Fracture zone 1 (m)	Fracture zone 2 (m)
IFP-1	PR	31.8–33.0	
	Gamma	Below 22.5 m	
	SN	20.0–32.0	
	LN	19.5–32.0	
	Litholog	22.9–36.1	
IFP-9	PR	–	28.4–33.5
	Gamma	17.6–23.2	28.0–33.5
	SN	18.0–23.0	27.5–33.5
	LN	–	27.6–32.4
	Litholog	19.7–21.3	29.9–33.5

PR, point resistance; SN, short normal; LN, long normal.

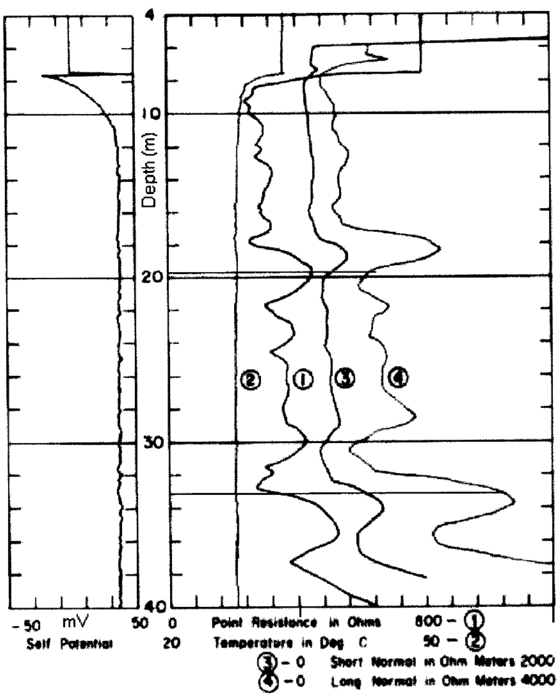

Figure 3. Well logs of well no. IFP-1.

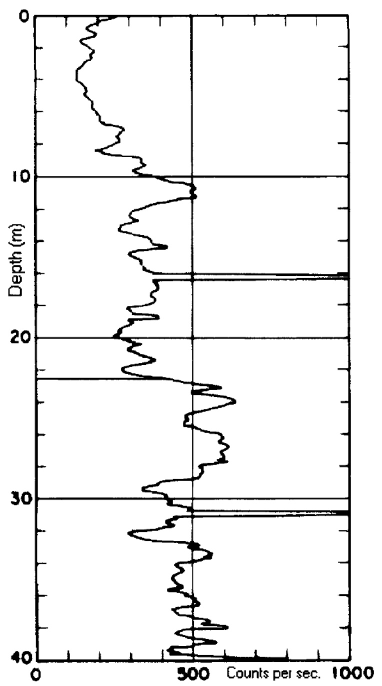

Figure 4. Gamma log of well no. IFP-1.

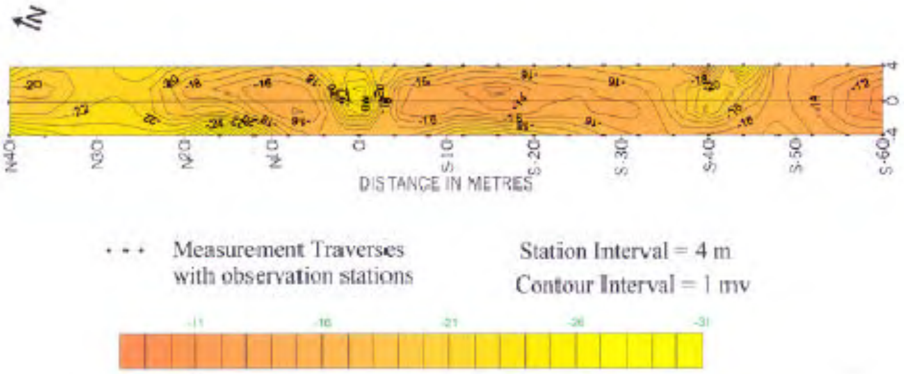

Figure 5. Surface SP contour map near IFP-1.

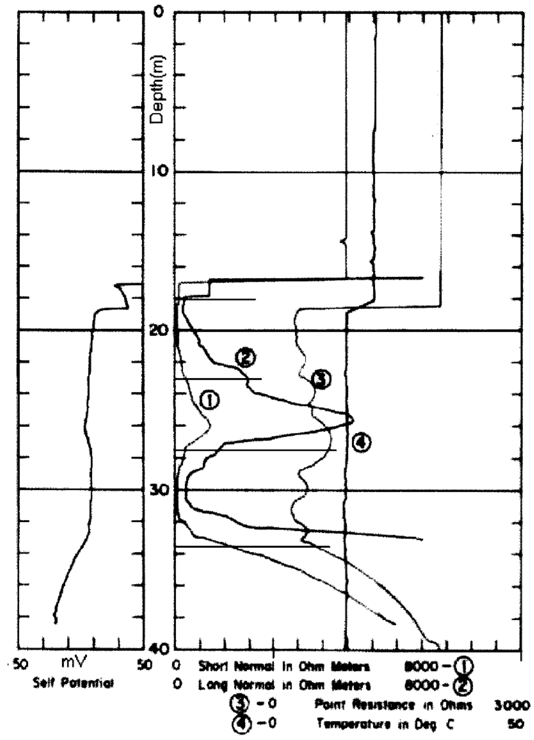

Figure 6. Well logs of well no. IFP-9.

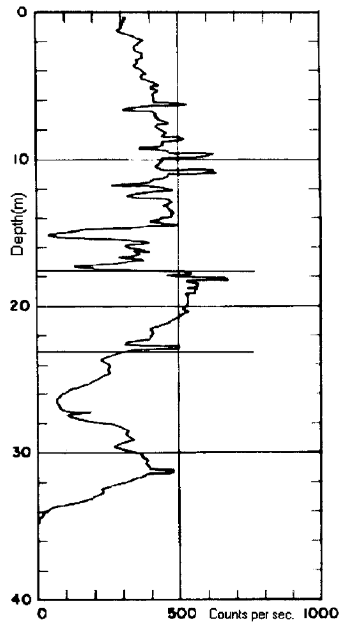

Figure 7. Gamma log of well no. IFP-9.

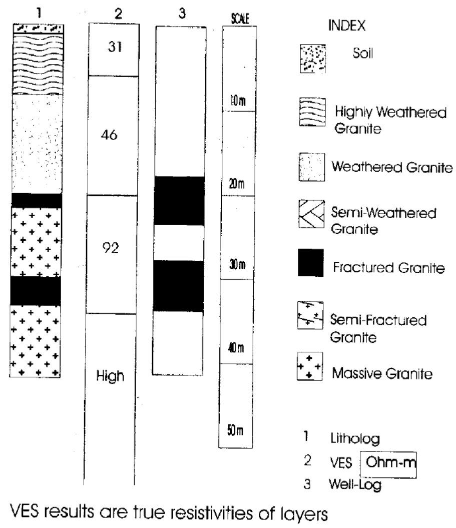

Figure 8. Comparison of litholog, VES and well log results for well no. IFP-9.

map around this well (Figure 9) shows a low equipotential near the borewell which may indicate a saturated fracture zone.

It is observed that the resistivity of fracture zone as determined from VES has varied from well to well. This is because these fractures even though appear as thick when observed while drilling, are in fact minute lines and the resistivity reduces only when they are saturated with water. Also, it is possible that the non-fractured part of the granite may vary in compactness from place to place and hence can give variable resistivities. These fracture zones are thin compared to the depth of occurrence, and occur between the semi-weathered zone and the bedrock. The effect of this zone is masked on the sounding curve and lies between these

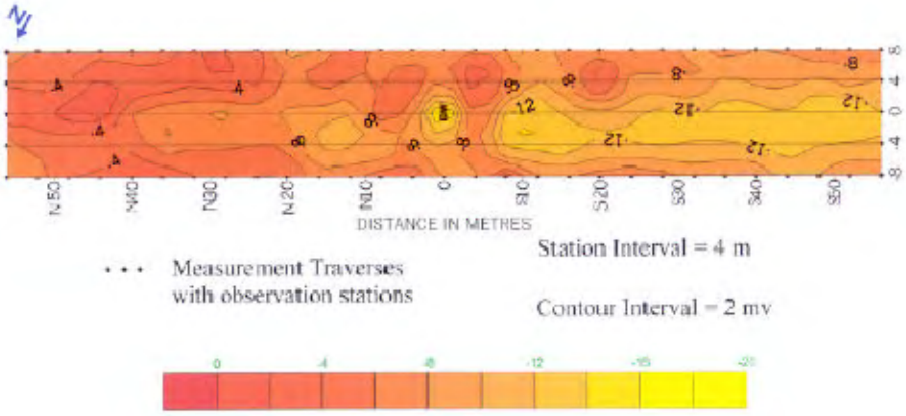

Figure 9. Surface SP contour map around well no. IFP-9.

two layers. Thus, the resistivity of this zone also depends on the resistivities of the bounded layers.

The results indicated that the thin fracture zones occurring at such a great depth, even though they are identified in well logging and seen in lithologs, are observed as thick single layers in the resistivity sounding curves with resistivity higher than that of the weathered granite and lower than that of the bedrock. At the same time, the surface SP investigations carried out around the borewell showed low anomalies near the wells indicating the presence of saturated fractures and the elongation of anomalies indicate the continuation of the fracture zones from the borewell. These SP results, though may not indicate the depth of occurrence of the fractures, definitely indicate the presence of fractures which are confirmed by the geophysical well logs. Similarly, the thin fracture zones are shown up as separate layers in the resistivity sounding, but appear as a single thick layer. Thus, the above results show the fracture zones identified by surface resistivity and SP measurements are confirmed by the subsurface lithologs and geophysical logs. Hence, it may be possible in a barren area to identify the fracture zone by carrying out surface resistivity and SP measurements, of course with closer observations.

1. Karous, M. and Mares, S., *Geophysical Methods in Studying Fracture Aquifers*, Charles University, Prague, 1988.
2. Zohdy, A. A. R., Eaton, G. P. and Mabey, D. R., *Application of Surface Geophysics to Groundwater Investigations*, U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, 1974, chap. D1, p. 86.
3. Murali, S. and Patangay, N. S., *Principles and Applications of Groundwater Geophysics*, P419, Association of Exploration Geophysicists, Hyderabad, India, 1998.
4. Chapman, M. J. and Lane, J. W., Proceedings of the Symposium on the application of Geophysics to Environmental and Engineering Problems, Keystone, Colo., 1996, pp. 833–842.
5. Johnson, C. D., Dunstan, A. H., Mack, T. J. and Lane, J. W., Jr., *Borehole-Geophysical Characterization of a Fractured-bedrock Aquifer*, Rye, New Hampshire, U.S. Geological Survey, 1999, Open-File Report 98-558, p. 61.
6. Mack, T. J., Johnson, C. D. and Lane, J. W., Jr., *Geophysical Characterization of a High-yield Fractured-bedrock Well*, Seabrook, New Hampshire, U.S. Geological Survey, 1998, Open-File Report 98-176, p. 22.
7. Schiavone, D. and Quanto, R., *Geoexploration*, 1984, **22**, 47–58.
8. Krishnamurthy, N. S., Ananda Rao, V., Negi, B. C., Kumar, D., Jain, S. C., Ahmed, S. and Dhar, R. L., Electrical Self-Potential and Mise-à-la-masse investigations in Maheshwaram Watershed, Andhra Pradesh, India, 2001, Technical Report No. NGRI-2001-GW-314.
9. Ahmed, M. V., *Geophys. Prospect.*, 1964, **12**, 49–64.
10. Parkhomenko, E. I., *Electrification Phenomena in Rocks*, Plenum Press, New York, 1971, p. 285.
11. Fitcherman, D. V., *Geophysics*, 1979, **44(2)**, 195–205.
12. Leary, P. C., *Geophys. J. Int.*, 1991, **107**, 615–627.
13. Dolan, S. S., Bean, C. J. and Riollet, B., *Geophys. J. Int.*, 1998, **132**, 489–507.
14. Subrahmanyam, K., Shakeel Ahmed and Dhar, R. L., Geological and Hydrogeological Investigations in the Maheswaram Watershed, R.R. Dist., Andhra Pradesh, India, Technical Report No. NGRI-2000-GW-292, 2000.
15. Krishnamurthy, N. S., Kumar, D., Negi, B. C., Jain, S. C., Dhar, R. L. and Ahmed, S., Electrical Resistivity Investigations in Maheswaram Watershed, Andhra Pradesh, India, Technical Report No. NGRI-2000-GW-287.
16. Krishnamurthy, N. S., Ananda Rao, V., Negi, B. C., Dewashish Kumar, Jain, S. C., Ahmed, S. and Dhar, R. L., Electrical Self Potential and Mise-a-la-masse Investigations in Maheswaram Watershed, Andhra Pradesh, India, Technical Report No. NGRI-2001-GW-314, 2001.
17. Krishnamurthy, N. S., Syama Prasad, B., Md Zaman, G., Anjaneyulu, G. R. and Jain, S. C., Well Logging for Identifying Fracture Zones in Boreholes in Maheswaram Watershed, Andhra Pradesh, India, Technical Report No. NGRI-2001-GW-322, 2001.

ACKNOWLEDGEMENTS. We are grateful to the Director, National Geophysical Research Institute for permission to publish this work. The Director and geologists of Andhra Pradesh State Groundwater Department provided the lithologs of drilled borewells for which they are acknowledged. The well logging was carried out using NGRI developed Well Logging equipment, for which Mr S. Narayana and B. Syama Prasad, Scientists, NGRI and Md. G. Zaman, Technical Officer, NGRI are acknowledged. Mr B. C. Negi, Technical Officer, NGRI is also acknowledged for his help in the field investigations. We are grateful to the anonymous reviewers for their comments to improve the manuscript.

Received 22 April 2002; revised accepted 19 January 2003