Localization of water bearing fractured zones in a hard rock area using integrated geophysical techniques in Andhra Pradesh, India

Sushobhan Dutta · N. S. Krishnamurthy · T. Arora · V. A. Rao · S. Ahmed · J. M. Baltassat

Abstract Knowledge of the existence of fracture zones, their extent, intensity and direction is very useful for assessing groundwater in hardrock regions and in this context geophysical methods are widely accepted as a powerful means of study. In the modern era of exploration, application of the Resistivity Imaging technique gives a new opportunity for groundwater study in hardrock regions. Exploration surveys were conducted at one of the important sites in Maheshwaram watershed, Andhra Pradesh, India with a multielectrode resistivity imaging system. To reduce the ambiguity of geophysical interpretation some complementary geophysical studies like ground Magnetic and VLF were also carried out.

A number of 2D resistivity images were prepared in a grid pattern, which clearly show the weathered and fractured zones in different parts of the study area. With the help of all 2D profiles a quasi-3D image has been created, which indicates the orientation and extension of the fracture zone in a horizontal as well as vertical direction in the study area. Strong agreement exists among the anomalies identified using the ground magnetic, VLF and resistivity imaging methods. The litholog data available in the study area also helps to interpret geophysical results to find a potential groundwater bearing zone in that area.

Résume La présence des zones fracturées, leur extension ainsi que leur intensité et direction est très utile pour l'évaluation des eaux souterraines cantonnées dans les roches dures. Dans ce contexte, les méthodes géophysiques sont largement acceptées comme des instruments performants pour l'étude de ce type de problème. La technique de "Resistivity imaging" offre une perspective nouvelle pour la prospection des eaux souterraines cantonnées dans les massifs rocheux. On a utilisé la méthode des images résistives multi électrodes pour la prospection d'un site important dans le bassin versant de Andhra Paresh de l'Inde. Afin de réduire l'ambiguïté de l'interprétation géophysique on a utilisé aussi des méthodes complémentaires comme la magnetométrie et VLF. Des images de résistivité réalisées dans des réseaux bidimensionnelles ont mis en évidence avec beaucoup de clarté les zones altérées et fracturées dans le site étudié. En utilisant toute les coupes 2D on a réalisé une image quasi-3D qui indique l'orientation et l'extension de la zone fracturé dans les plans verticaux et horizontaux. Il y a un bon accord entre les anomalies identifiées par la magnétométrie, la VLF et la méthode des images résistive. Les données de litholog disponibles dans la zone étudiée permettent de mieux interpréter les résultats géophysiques pour mettre en évidence les potentielles hydrostructures dans le site étudié.

Resumen El conocimiento de la existencia de zonas de fractura, su extensión, intensidad y dirección, es muy útil para evaluar el agua subterránea en regiones con rocas duras y en este contexto los métodos geofísicos son ampliamente aceptados como medios de estudio poderosos. En la era moderna de la exploración, la aplicación de la técnica de proyección de imágenes de resistividad, da una nueva oportunidad para el estudio del agua subterranean en regiones con rocas duras. Las investigaciones exploratorias fueron ejecutadas en uno de los sitos importantes en la cuenca de Maheshwaram,Andhra Pradesh, india, con un sistema multielectródico de resistividad con proyección de imágenes. Para reducir la ambigüedad en la interpretación geofísica, también fueron ejecutados algunos estudios geofísicos complementarios, como magnetometría de superficie y VLF.

Un número de imágenes de resistividad 2D se preparó en forma reticular, las cuales muestran de manera clara las zonas fracturadas y meteorizadas en diferentes partes del área de estudio. Con la ayuda de todos los perfiles 2D, fue creada una cuasi - imagen 3D, la cual indica para el área de estudio, la orientación y extensión de la zona de fracturas, tanto en dirección horizontal, como en la vertical. Hay una fuerte coincidencia entre las anomalías identificadas mediante el uso de la magnetometría de superficie, el método

Received: 19 January 2005 / Accepted: 25 March 2005
Published online: 2 September 2005

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DOI 10.1007/s10040-005-0460-7

VLF y el de la proyección de imágenes de resistividad. La información litológica que se pudo obtener en el área de estudio, también ayudó a interpretar los resultados geofísicos, para encontrar en ésta área una zona que potencialmente contenga agua subterránea.

Keywords Fracture · 2D Resistivity imaging · VLF · Quasi-3D resistivity imaging.

Introduction

Geological features like fault zones, fractures and joints, created through different tectonic or chemical activities generally store and transport groundwater in the subsurface of a hard rock environment. Hard rock areas of India generally consist of granite or granite gneiss overlain by a variable thickness of weathered material, a regolith, produced by the in situ weathering of the basement rock (Acworth 1987). In a groundwater study, the main goal of geophysical exploration is to map the geological environment in which water can exist. Electrical resistivity sounding has been applied for many decades to determine the thickness and resistivity of the layered media, but the recent development of the resistivity imaging technique introduces a new era in groundwater exploration. Grifiths and Barker (1993), Mendoza et al. (2000), Ionnis et al. (2002), Barker et al. (2003) successfully used the resistivity imaging technique for solving geological problems in hard rock areas. In this resistivity survey the Wenner array configuration, using 48 electrodes with an inter electrode spacing of 8 m, provided 360 data points, which were collected within approx. 30 min. This acquisition time varies and it depends upon the number of stacks, pulse duration etc., related to the quality of data. The collected apparent resistivity data was transferred to a microcomputer and after necessary processing the data was inverted by the least square inversion technique to get the 2D model resistivity section. By combining the entire 2D resistivity models a quasi-3D (Dahlin and Loke 1997) approach was taken to build up a 3D variation of resistivity in the study area. Additional measurements with ground magnetic and VLF electromagnetic methods were carried out to give additional constraints, which were used in the final geological interpretation of the results.

Hydrogeology

The study area is in the main Maheshwaram watershed of about 60 km^2, situated nearly 30 km south of Hyderabad (Fig. 1) in India.

It lies between the geographical coordinates of longitude: 78°24′30″ E–78°29′00″ E and latitude 17°06′20″ N–17°11′00″ N with the average elevation of 620–600 m above msl. The main area is further divided into several small watersheds. The Mahabbatnagar area is one of those small watersheds where this study was carried out.

The simplified geological profile (Fig. 2; Marechal et al. 2004) shows the common geological setting of the hard rock environment in Maheshwaram watershed. The watershed is basically underlain by pink and gray colored medium to coarse-grained granites of Archean age. In which the upper part is subjected to weathering and fracturing and makes up the main aquifer in the watershed. On the NE side of the study area there is a dug well, which shows the existence of weathering/fractures in the subsurface formation. In the whole watershed the depth to the water level varies from 11 m to 20 m below the ground surface. Study of aerial photographs and land sat images show that the watershed is traversed by lineaments in several places represented by dykes, quartz veins and shear zones. Throughout the watershed these lineaments are manifested by the presence of high yield (ranging from 1,000 gph to 5,000 gph) borewells aligned with the lineaments. Also in the study area some surficial features were observed which indicates the existence of a dolerite dyke trending in the SW-NE direction.

Methodology

Resistivity imaging

Resistivity imaging is a fully automated technique that uses a number of electrodes connected by a multicore cable.

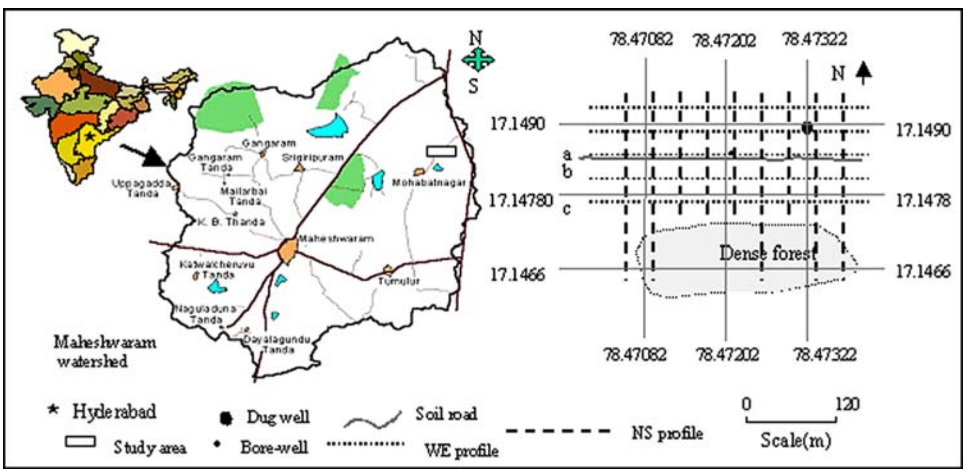

Fig. 1 Location map and survey layout of the study area

 DOI 10.1007/s10040-005-0460-7

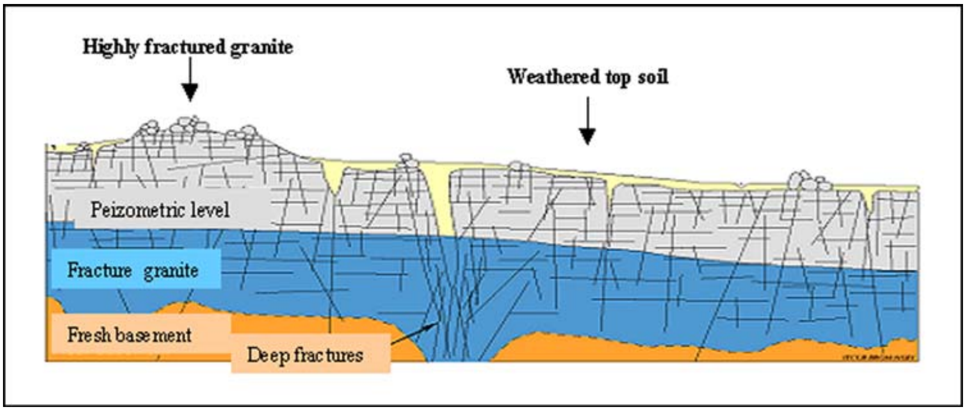

Fig. 2 Common geological setting of the Maheshwaram watershed in cross section

The resistivity meter controls the positions of current and potential electrodes through a microprocessor controlled electronic module. Before starting the field procedure the specific electrode configuration along with the spacing between the electrodes and all other necessary information is fed to the meter through a computer. Data is then collected automatically. Field data can be processed in several stages by using commercially available software (prosys-geotomo software); these apparent resistivity data can be inverted to produce a modeled resistivity 2D section along the profile. By using the proper survey pattern and processing of data, a 2D as well as a 3D picture of the subsurface can be obtained.

In the present study 2D resistivity imaging was carried out along nine NS and five WE profiles in a grid pattern (Fig. 1). Data were collected with the Syscal Jr. Switch 48 (Iris Instrument) system with 48 electrodes grounded with an electrode interval of 8 m. Resistivity data were collected with the Wenner configuration. For improving signal to noise ratio a single point data was collected with maximum 10 stacking. The processing was performed by filtering out the bad quality data and the fresh data were used as input to RES2DINV (Loke and Barker 1995), which is an inverse program that estimates a 2D resistivity image of the earth. RES2DINV is a least-squares inversion technique that uses smoothness constraints (DeGroot-Hedlin and Constable 1990; Ellis and Oldenburg 1994). The inversion procedure estimates the smooth model that fits the data to a given error level. Here in all the inversion models RMS error (difference in calculated and apparent resistivity values) was less than 3%. A quasi-3D approach was taken to observe the resistivity variations in all three directions. There are many works on fracture detection using 2D resistivity imaging (Barker et al. 2003) but this quasi-3D method clearly represents the 3D variation of subsurface resistivity of the study area, where an actual 3D resistivity survey is a difficult job. Modeled resistivity data have been sorted out from different depth levels of each WE and NS profile and a number of horizontal resistivity sections were created by merging the entire cross profiles at a specified depth level.

Results

The modeled resistivity vertical section shown in Fig. 3 represents three among the five WE profiles with 40 m separations. The rest of the profiles, not shown here, were used for preparing the 3D picture shown in Fig. 4. All the resistivity images with Wenner configuration show a clear 2D resistivity variation in the subsurface. In Fig. 3a, the image is from the base line profile which passes through the middle portion of the field area and the two others i.e. 3b and c are from the southern part.

This quasi-3D image (Fig. 4) clearly shows the weathered and fractured zone (marked as ‘F’) extends in the NW-SE direction and meets an obstruction in the southern part, indicated by a high resistivity structure trending in the NE-SW direction.

VLF-Tilt angle method

By using far field approximation of Maxwell equations, VLF (very low frequency) is one of the widely used electromagnetic techniques in groundwater prospecting (Bernard and Valla 1991; Benson et al. 1997; Hautot et al. 2002). The source used by this method is electromagnetic radiation generated in the frequency range of 15–25 kHz by the powerful military radio transmitters. The radiation from these transmitters contains both electric and magnetic field components, in a vertical plane in the propagation direction and at a right angle to the direction of propagation in a horizontal plane, respectively. In the present study the VLF tilt angle method was employed. The magnetic component was of interest for this study. The main principle of the VLF tilt angle method is available in many of the electromagnetic textbooks (Kearey et al. 2002). The tilt angle θ is the inclination from the horizontal of the major axis of the polarization ellipse (Paterson and Ronka 1971) and is defined by Smith and Ward (1974)

$$\theta = 0.5 \tan^{-1}[\pm\{2(H_z/H_x)\cos\Delta\phi\}/\{1-(H_z/H_x)^2\}]$$

where, H_z and H_a are the amplitude of the vertical and horizontal component of the magnetic field respectively and $\Delta\varphi$ is the phase difference between them. The tangent of the tilt angle is a good approximation to the ratio of the real component of the vertical secondary magnetic field to the local horizontal magnetic field (Paterson and Ronka 1971) and is called the real anomaly, expressed as a percentage.

DOI 10.1007/s10040-005-0460-7

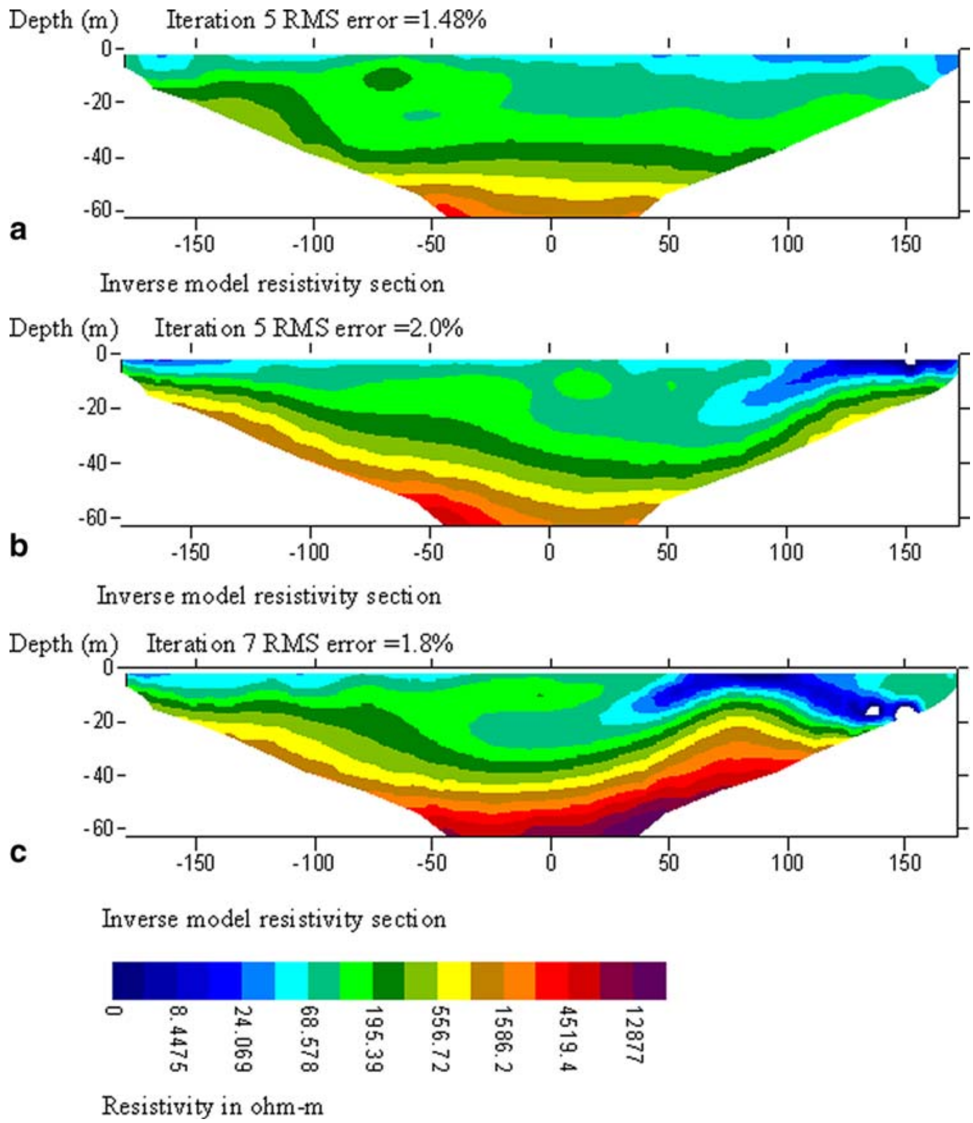

Fig. 3 **a**, **b** and **c** represent 2D resistivity images of different WE lines

The field procedure with the modern VLF instrument (T-VLF, Iris Instrument) is rather simple. It has three coils with their axes at right angles which can thus detect the signal whatever its direction, and find the null orientation electronically and automatically. This instrument can measure dual frequency mode signals coming from two distant military transmitters simultaneously. The depth of investigation of the method depends on the resistivity of the medium (Bernard and Valla 1991) and the frequency, which is constant here.

The 22.3 kHz signal from the transmitter located in Australia, was used as the source for the VLF measurement. Data were collected every 8 m of interval along five traverses in a West-East direction. Throughout the measurement the transmitter signal reception quality was 60% of the full signal scale.

Figure 5 shows there is a large tilt angle variation (−15 to +75%) in the study area. The area corresponding to low tilt angle values may represent a conductive zone, which can be confirmed after comparing with electrical resistivity information.

Magnetic mapping

The purpose of this study was to observe the variation of the earth's magnetic field caused by different magnetic susceptible zones, such as intrusive dykes in the study area and to identify a probable 2D structure favorable for groundwater flow. In a hard rock terrain like Maheshwaram, groundwater flow, sometimes controlled by the presence of different 2D structures and in this context ground magnetic intensity variation, may give reliable response to the existence of such 2D structures. In the present study magnetic responses were taken at about 190 stations with a Proton Precision magnetometer (Terra-Science, model TSPM-A). A positive diurnal variation has been observed throughout the measurement period. The resultant magnetic map given in Fig. 6 shows a smooth variation of magnetic intensity (42,140–43,000 nT) except

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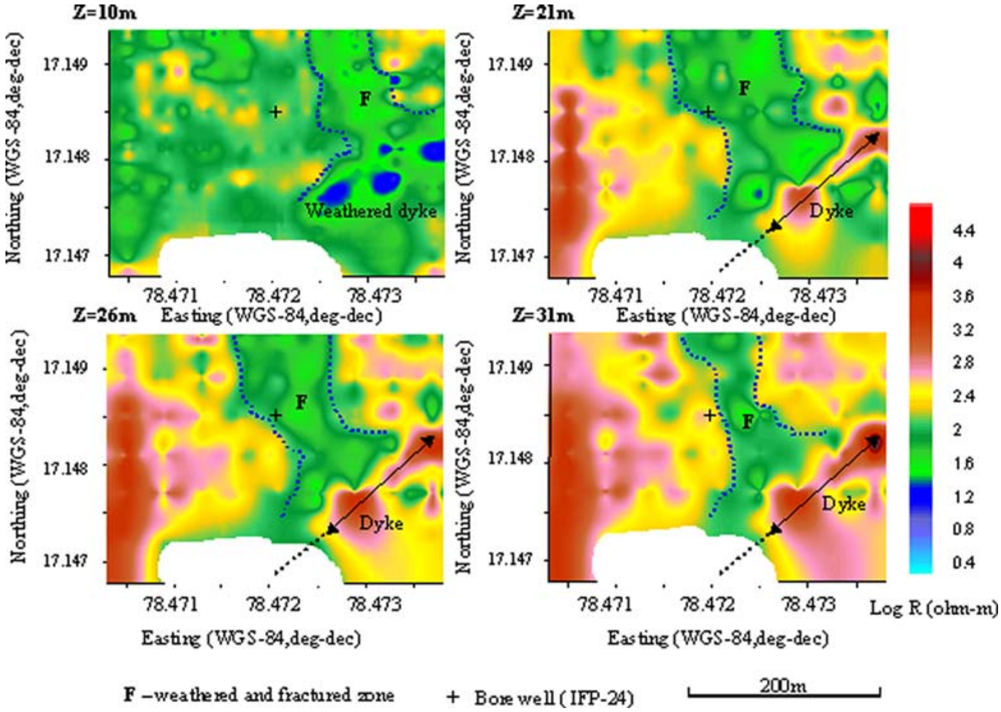


Fig. 4 A quasi-3D representation

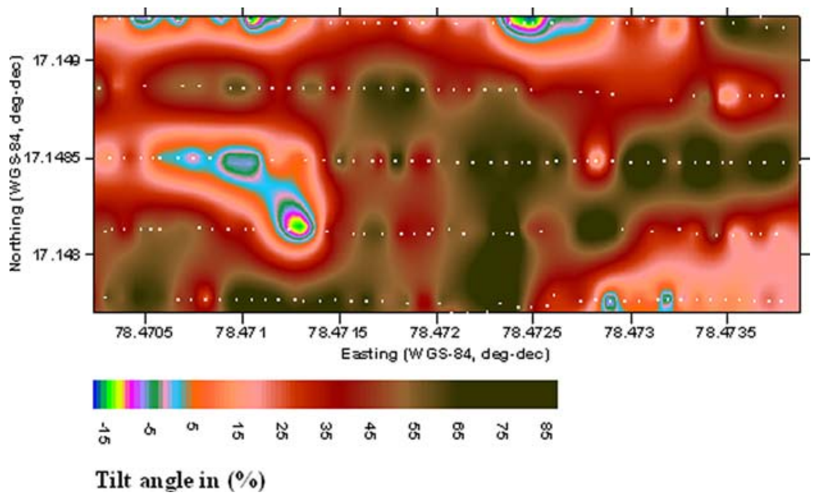


Fig. 5 Tilt angle variation (transmitter freq. −22.3 kHz)

at a few locations. In the southern part an extremely high anomalous zone, could be a dyke present in the NE-SW direction.

Litholog information

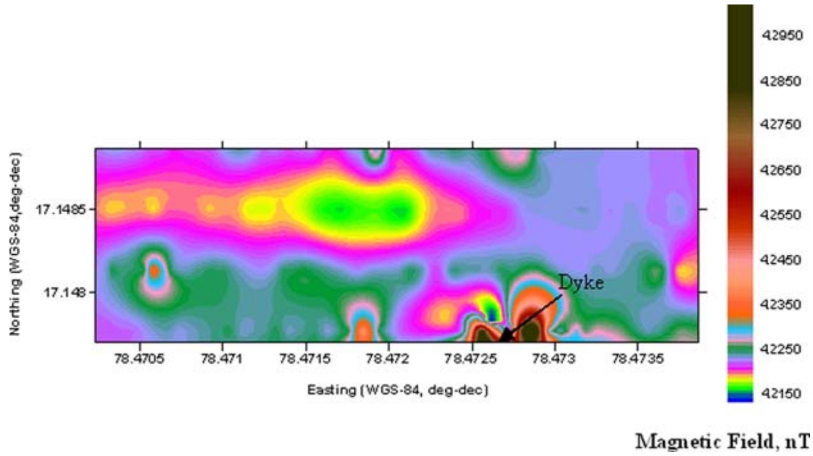
Litholog data collected from an existing bore hole (IFP-24) in the study area clearly reveals the distribution of the weathered and fractured rocks in the subsurface geology up to a certain depth. The degree of weathering and fracturing is shown in Fig. 7. The quasi 3-D picture also shows the continuation of the layer to this depth. Though it appears as a single layer, the fractures may not continue throughout the zone but may be intermittent in the layer. This can be observed from the 2D sections, which show different resistivity zones indicating the changes in the lithology (intermittent fractures) caused by the saturation of water within the fissures/fractures.

Interpretation

Finally, a qualitative interpretation is obtained by combining the results of all three methods as there exists a good correlation between them. In all the 2D resistivity sections (Fig. 3), low resistivity corresponds to weathered and fractured granite up to the depth of around 45 m. The trend of high resistivity values towards the western side may imply that the basement is becoming shallower towards that side; this is clear in the quasi-3D image. Also in the eastern part of the two sections, ‘b’ and ‘c’ of Fig. 3 there is a highly resistive zone (around 5,000 Ohm-m), which is

DOI 10.1007/s10040-005-0460-7

Fig. 6 Total geomagnetic field variation in the study area



much greater than in the western part. So a common feature in both imaging profiles shows that a low resistivity zone exists as a basin-like structure between the two high resistivity zones of the western and eastern sides. By observing the sections 'b' and 'c' initially it seems that in the eastern part the basement is also shallower and comparatively compact because resistivity on this side shows a high value, however the magnetic map (Fig. 6) presents a mystery. It shows that there is a high magnetic susceptible zone in the SE part of the study area, which was also observed as a higher resistivity zone in the imaging section. Both the magnetic as well as quasi-3D image show this structure is a dolerite dyke (supported by transported material seen in the area) and is trending in the NE-SW direction. However, in the western side of the study area there is no such strong magnetic anomaly observed, which implies the high resistivity observed in the western side corresponds to shallow granite basement. Due to inaccessibility there is no geophysical information further south, so only on the basis of the anomaly distribution of the transported dolerite materials on the surface, it can be inferred that this dyke may continue further in the SW direction. A low tilt angle is observed over the dyke (Fig. 5) and image profiles show the upper part of the dyke is weathered and so conducting. So it can be inferred qualitatively that the secondary field response for the VLF method is derived from a shallow conducting zone.

2D and quasi-3D resistivity images clearly show a weathered and fractured zone exists in the middle position of the study area as a linear feature in a NW-SE direction (zone 'F' bounded by a blue dotted line in the 3D image in Fig. 4 and also extending into the deeper subsurface (Fig. 4 shows only up to 31 m depth) similar to a basin structure. The quasi-3D image shows this structure is not exactly vertical but deepening on the western side. The borewell (IFP-24) intercepts this fractured zone at about the 10–20 m depth level where this zone is widest. Drilling results also show water was encountered at 24 m depth which rose to a static water level of 13 m depth. The pumping test results show a transmissivity of 36 m^2/day and a yield of 6,000-lph. At present (Nov. 2004) the water level of this borewell is 16 m. The most important feature in this linear zone is that it is

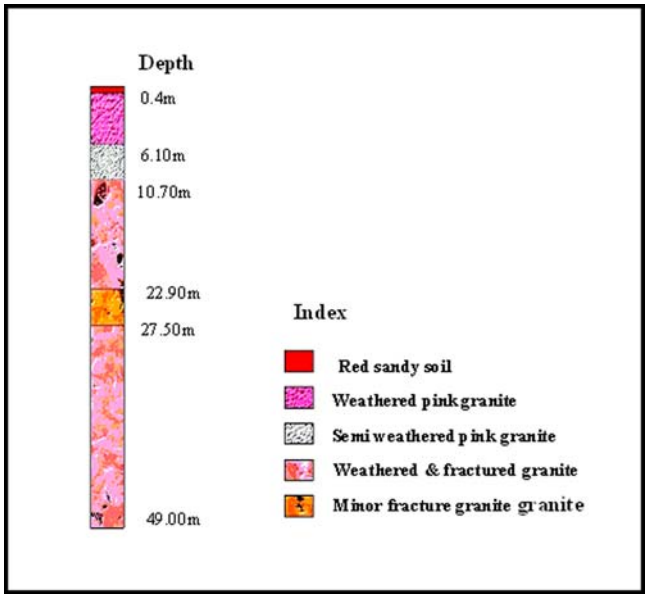


Fig. 7 Litholog section of bore well IFP-24

cutoff by the NE-SW trending dolerite dyke (confirmed by the magnetic map) and becomes wider parallel to the dyke direction. In a hard rock environment like Maheshwaram this weathered and fractured zone can have a huge importance to store and transport groundwater and act as a granitic aquifer. The resistivity imaging result is well supported by the litholog data, which adds some additional information relating to the local lithology so these electrical images can be converted to a geological section. The litholog section in Fig. 7 shows that the upper part of the basement is weathered and fractured to a greater and lesser extent at different depths, which can be a strong support for this qualitative combined interpretation.

Conclusion

The resistivity imaging technique is a powerful tool and provides a new opportunity in groundwater exploration. Compared to any other conventional geophysical tech-

 DOI 10.1007/s10040-005-0460-7

niques this method is economical and provides detailed information by imaging the subsurface very precisely. The geoelectrical investigation along with complementary surveys of ground magnetic and VLF techniques revealed the subsurface geological setting, which plays an important role in groundwater flow.

The study shows that a quasi-3D approach successfully describes the 3D variation of resistivity values in an area, which is not accessible for a full 3D survey. The interpreted results show that the area consists of several lithologic layers, the bottom most layer is the compact basement with the highest resistivity. Groundwater is mainly confined in the weathered and fractured zones in a semi-confined aquifer system.

Acknowledgement The Authors express their thanks to the Director, NGRI for his kind permission for carrying out the study. This work was carried out in a project partly funded by the Indo-French Center for Advance Research (IFCPAR), New Delhi.

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