5 Geophysical Exploration

5.1 Introduction

Following the investigations by aerial photographic and satellite remote sensing techniques, geophysical survey is carried out to ascertain the subsurface geological and hydrogeological conditions and aquifer characteristics. Various petro-physical properties utilized in geophysical exploration include electrical resistivity, electrical conductivity, density and elasticity (influencing seismic velocity), electrical permittivity (dielectricity), magnetic susceptibility, and radioactivity. Geophysical methods have the potential to predict distribution and flow of groundwater including sites of hazardous substances in a cost-effective manner. Further, as these methods are non-invasive, as compared to the direct conventional methods (for example, water sampling etc.), they do not disturb the water flow regime and are able to predict parameter distribution more realistically. Depending upon the scale of operations, geophysical surveys can help delineate regional hydrogeological features or even pin-point locations for drilling of water-wells. Geophysical surveys can appreciably reduce much more costly infructuous drilling operations. Details of geophysical methods can be found in several standard texts (e.g. Dobrin and Savit 1988; Parasnis 1997; Telford et al. 1999; Kearey et al. 2002). Geophysical applications specifically for groundwater are reviewed by deStadelhofen (1994), Beeson and Jones (1988), Kirsch (2006) and Ernstson and Kirsch (2006b) among others.

It is essential that geophysical surveys are not undertaken in isolation but are fully integrated with geological, hydrogeological and drilling. A reliable interpretation of geophysical survey data has to take into account prior knowledge of subsurface geology of the area. Therefore, at the outset, these surveys should be carried out at locations where the subsurface geology is better known. This will provide useful controls for interpretation of geophysical data in terms of subsurface geology, which can be later extrapolated to other similar areas.

5.2 Electrical Resistivity Methods

Electrical techniques, especially the resistivity surveys, are the most popular of geophysical methods for groundwater surveys because they often give a strong response to subsurface conditions and are relatively cost-effective (Ernstson and Kirsch 2006a). A combination of techniques can prove particularly useful and many studies are now carried out using a combination of resistivity sounding and electromagnetic traversing.

5.2.1 Basic Concepts and Procedures

Resistivity is defined as the resistance to electric current offered by a unit volume of rock and is a characteristic property of the medium in that state. It is based on the fact that electrical resistivity of a geological formation is dependent upon the material as well as the bulk porosity, degree of saturation and type of fluid. Since electrical resistivity of common minerals is very high, the electrical current flows through the pore fluid (water). The electrical resistivity of water-saturated clay-free material is given by the Archie's Law:

$$\rho_{aquifer} = \rho_{water} \times F \tag{5.1}$$

where F is the formation factor and $\rho_{aquifer}$ and ρ_{water} are the specific resistivities of aquifer and pore water

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Table 5.1 An overview of physical properties of saturated and unsaturated materials likely to be found in geophysical prospecting of groundwater. (Kirsch 2006)

	Seismic	Geoelectric, Electromagnetic		GPR	
	P-wave velocity ($m\,s^{-1}$)	Resistivity (Ωm)	Conductivity ($mS\,m^{-1}$)	Permittivity (relative to air)	Wave velocity ($cm\,ns^{-1}$)
Gravel, sand (dry)	300–800	500–2000	0.5–2	3–5	15
Gravel, sand (saturated)	1500–2000	60–200	5–17	20–30	6
Fractured rock	1500–3000	60–2000	0.5–17	20–30	6
Solid rock	>3000	>2000	<0.5	4–6	13
Till	1500–2200	30–60	17–34	5–40	6
Clay	1500–2500	10–30	34–100	5–40	6

respectively. The formation factor F depends upon porosity, pore shape, cementation etc. The Archie's Law is not valid if grains are conducting (e.g. clay-rich matrix) or if pore water is highly resistive. The electrical resistivity of a dry formation is much higher than that of the same formation when it is saturated with water (Table 5.1).

Resistivity of the ground is measured by injecting current into the ground and measuring resulting potential difference at the surface across selected electrode positions (Fig. 5.1). The data on current flow and potential drop are converted into resistivity values. In case of an inhomogeneous earth, the measured resistivity is influenced in varying proportions by material from a wide depth range in the region covered by the electrodes (Fig. 5.2) and therefore, the field resistivity values are apparent (ρ_a) rather than true.

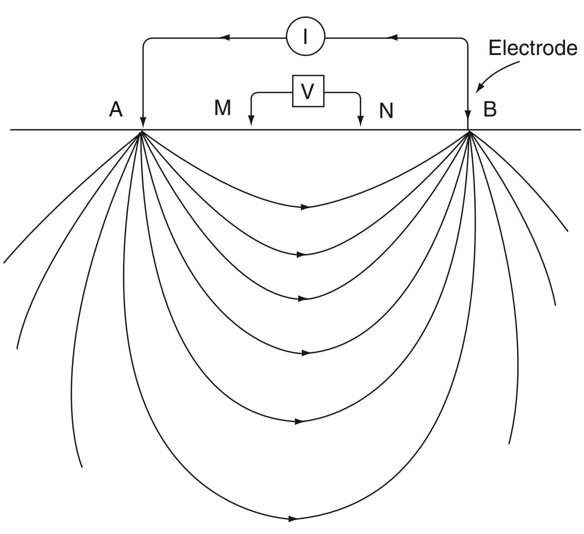

Fig. 5.1 Basic configuration in electrical resistivity surveys. *A* and *B* are current electrodes; *M* and *N* are potential electrodes

The arrangement of the four electrodes on the ground (two current and two potential) is referred to as the electrode 'array' or configuration. Most commonly used electrode configurations are Wenner and Schlumberger types (Fig. 5.3). In Wenner array, the four electrodes are placed collinearly and are equally spaced. In Schlumberger array, the electrodes are collinear but the distance between the two inner potential electrodes is very small in comparison to the distance between the two outer current electrodes. The apparent resistivity (ρ_a) is calculated as:

$$\rho_a = 2\pi\ aR \quad (\textit{Wenner array}) \tag{5.2}$$

$$\rho_a = \pi\left(L^2/2l\right)R \quad (\textit{Schlumberger array}) \tag{5.3}$$

where a, L and l are distances as shown in Fig. 5.3 and R is the measured resistance (voltage/current) in each case. Broadly, the depth of investigation of a resistivity survey is directly proportional to the electrode separation, and increases with increasing electrode spacing (Fig. 5.4). There is no single well-defined depth

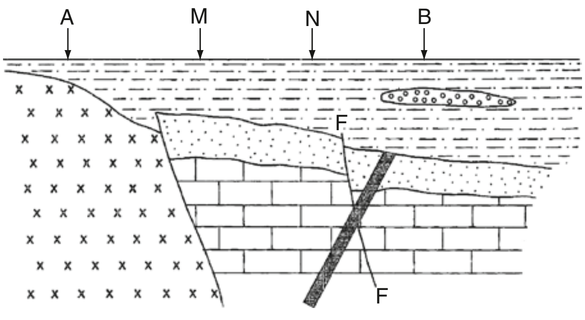

Fig. 5.2 Inhomogeneous geological features at depth often form the target for electrical resistivity surveying

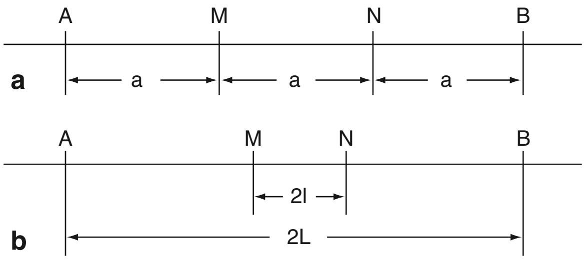

Fig. 5.3 Electrode configurations for collinear resistivity survey. **a** Wenner configuration and **b** Schlumberger configuration

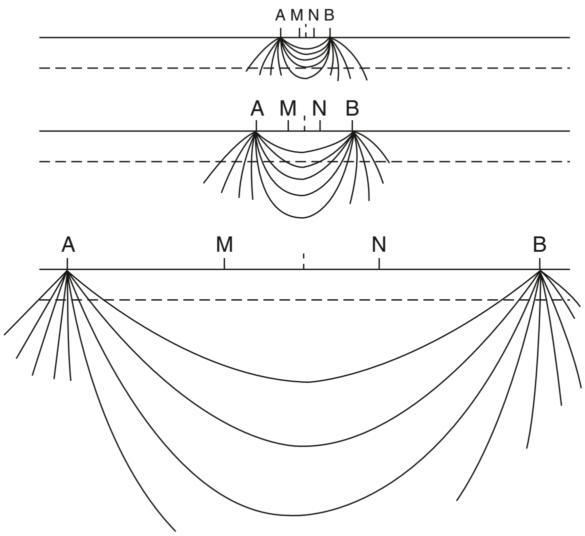

Fig. 5.4 The depth of investigation increases with increasing electrode seperation

to which a resistivity measurement can be assigned. Median depth (0.17–0.19 × distance between the two outer current electrodes) is considered as the most useful concept to describe the depth of penetration.

In geoelectrical methods, a distinction is required to be made whether one has to deal with horizontally layered earth (e.g. sedimentary terrain), or with elongated 2-D bodies like fractured zones and dikes, or with arbitrarily shaped structures (e.g. lenticular bodies or karst caves etc.). Accordingly 1-D (VES), 2-D (electrical imaging) and 3-D geoelectrics is used.

Vertical Electrical Sounding (VES) is applied to near horizontal layered medium, e.g. sedimentary terrain or weathered zones over hard rocks. It is used to determine variations in electrical resistivity with depth. In VES (also loosely called electrical drilling), the distances between electrodes are increased so that the electric current penetrates to deeper and deeper

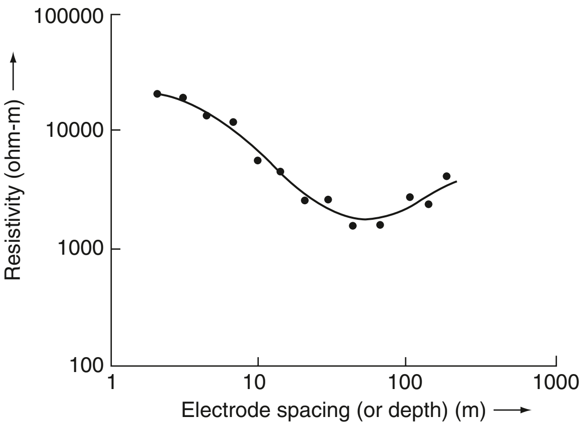

Fig. 5.5 Examples of electrical resistivity curves for depth sounding

levels, which allows resistivity measurement of a deeper and larger volume of the earth (Fig. 5.4). The apparent resistivity is plotted against the electrode separation (Fig. 5.5). The task of defining layers in a field survey is quite intricate as several interpretation methods, many involving curve-matching with standard curves, have been developed to provide better delineation of resistivity layers in various conditions (e.g. Koefoed 1979; Bhattacharya and Patra 1968). The interpretation result of a VES survey is the number of layers, their thicknesses and resistivities. In regular sedimentary sequences VES may be more reliable. However, in areas of unconsolidated sediments with rapidly varying thickness, borehole data is valuable in fixing model parameters for obtaining realistic depth estimates. The interpretation can be refined through forward or inverse modelling. Standard interactive computer programs executable on PC's are now available for this purpose. Normally, three to four distinct layers are about the maximum number for a reasonably accurate interpretation of a resistivity sounding curve. The VES remains an extremely powerful technique for delineation of regolith thickness which is vital when the saprolite is potentially thick (>20 m). Table 5.2 gives aquifer prospect as related to resistivity of layered regolith. However, VES is not an appropriate tool for detecting localized fracture systems.

Resistivity mapping is carried out for delineating near surface resistivity anomalies caused by for example, fracture zones, cavities or waste deposits. Any common electrode configuration can be applied.

Table 5.2 Aquifer prospect as related to resistivity (ohm metre) of layered regolith. (After Bernardi et al. in Wright 1992)

0–20	Clays with limited prospect (or saline water)
20–100	Optimum weathering and groundwater prospect
100–150	Medium conditions and prospect
150–200	Little weathering and poor prospect
>250	Negligible prospect

The electrode separation is kept constant and moved along profiles while apparent resistivity is measured. This enables gathering resistivity data over an area for a chosen depth of investigation. Contouring of resistivity data and interpretation provides information on variation in bedrock/soil type, spatial variation in depth of weathering and moisture content etc. Interpretation is generally done qualitatively by locating structures of interest. This method is commonly used for reconnaissance, after which detailed study in the selected target area is made through other geoelectrical methods. Figure 5.6 shows resistivity profiling across a lineament in Zimbabwe.

As mentioned above, formation resistivity is influenced by mainly porosity (primary and secondary), degree of saturation and type of fluid. Therefore, it varies with degree of weathering and seasonal fluctuations in water salinity. In an area, low resistivity values may correspond to clays, highly fractured rocks, or saline sand. On the other hand, high resistivity values may correspond to tight (low porosity) rocks, fresh-water-bearing sands or a relatively clean (clay-free) zone.

Normally, it is difficult to distinguish between permeable and impermeable fractures through electrical methods because their electrical properties are similar, especially when the impermeable fractures are filled with gouge, clay minerals or other alteration products. Such ambiguities which may occur are natural to geophysical methods. Therefore, it is very necessary that geophysical data are interpreted with adequate control on surface and subsurface geology, which may be available from exposures and/or boreholes.

Electrical tomography, or electrical imaging, is a surveying technique for areas of complex geology. In 2-D resistivity imaging, resistivity sounding and profiling are combined in a single process. It is assumed that the resistivity of the ground varies only in the vertical direction and one horizontal direction, i.e., along the profile (assuming that there is no resistivity variation perpendicular to the profile direction). It involves measuring a series of constant separation traverse with the electrode separation being increased with each successive traverse. The measured apparent resistivity values are plotted on a depth section immediately below the centre of the electrode arrangement. The apparent resistivity values are contoured to produce a 'pseudosection', which reflects qualitatively the spatial variation of resistivity in the cross-section. Thus, the method is used to provide detailed information both

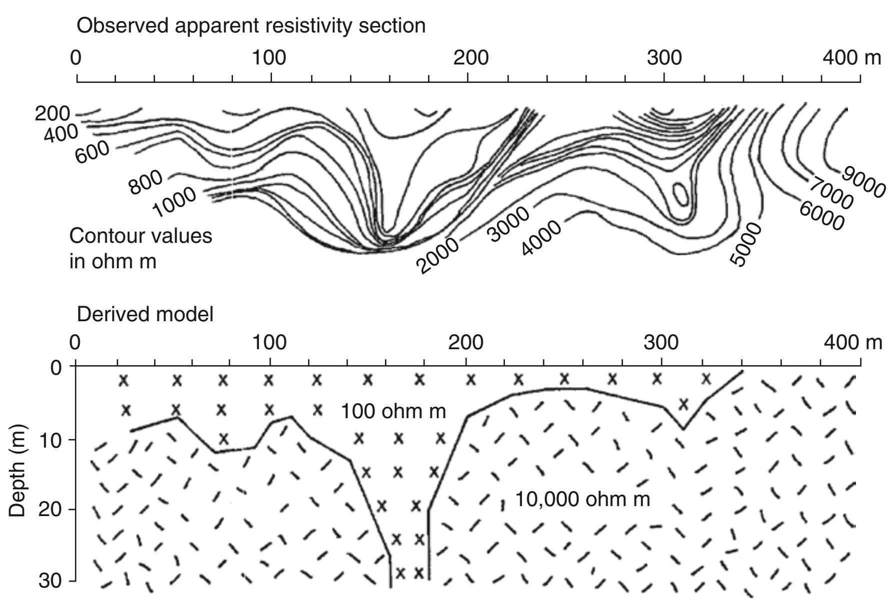

Fig. 5.6 Resistivity traverse data across a lineament in Zimbabwe, with a 2-layer interpretation. (After Griffiths in Carruthers and Smith 1992)

laterally and vertically along the profile so that more complex geological structures can be investigated.

The 3-D resistivity surveying is more complex, time consuming and expensive. A multielectrode (upto 256 and more) resistivity meter with switching is used. Several depth levels may be investigated by increasing the electrode spacing. The observed data of 2-D resistivity survey (also called resistivity imaging) are displayed as a pseudo-section along the profile in which geological–hydrogeological features can be interpreted.

5.2.2 Delineation of Rock Anisotropy

Rock anisotropy due to foliation, bedding, fractured zones etc., invariably leads to electrical anisotropy such that the resistivity in a direction parallel to the strike is generally lower than that in the perpendicular direction. Mapping of resistivity anisotropy is therefore extremely important. There are two methods for delineating rock resistivity anisotropy—square array configuration and azimuthal resistivity survey.

5.2.2.1 Square Array Configuration

This is specially designed for mapping rock resistivity anisotropy and has been widely applied. In this method, the electrodes are arranged to form a square with a pre-selected length side (A) (Fig. 5.7). The

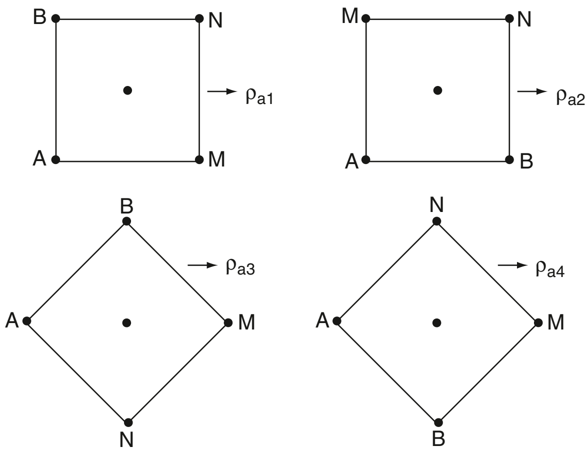

Fig. 5.7 Square array configuration: the apparent resistivity values are measured by rotating the electrodes in four configurations: ρ_{a1}–ρ_{a4}

apparent resistivity is assigned to the mid point of the square and is calculated as:

$$\rho_a = K\,R \tag{5.4}$$

where K is called the geometric factor of square ($=2\pi A/2-\sqrt{2}$), R is the resistance measured. At each location, the square array is rotated by 45° successively, and four apparent resistivity values (ρ_{a1}–ρ_{a4}) are measured. For a single-set of saturated steeply dipping fractures, the square-array method gives apparent resistivity minimum oriented in the same direction as the fracture strike (Fig. 5.8), and the data set can be

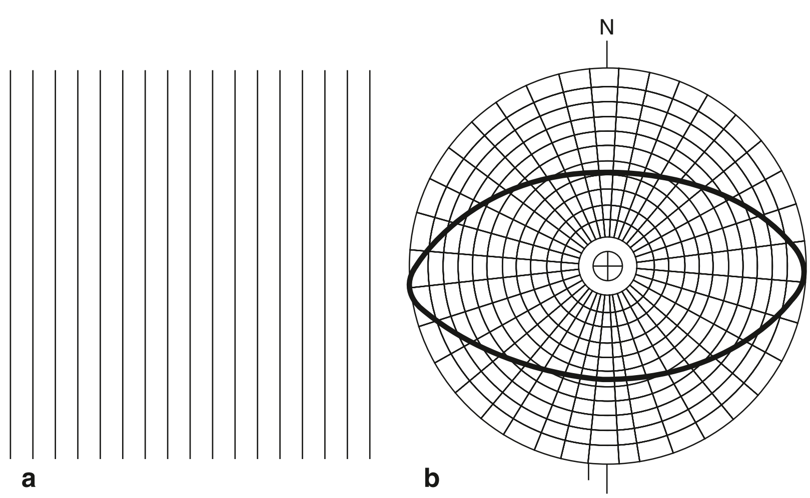

Fig. 5.8 **a** The case of one set of predominant fractures, and **b** the resulting square array azimuthal resistivity figure

used to compute resistivity anisotropy and approximate strike of the fractured zone. For example, the square array azimuthal resistivity survey in the crystalline rocks at Mirror Lake, New Hampshire, USA, Cook (2003) showed that the minimum resistivity is in N 30° direction, which is also found to be the fracture orientation as revealed from mapping in adjacent outcrops overlain by glacial deposits. The main advantages of the square-array method lie in its higher sensitivity to anisotropy as compared to co-linear arrays, and its requirement of less surface area for a given depth of penetration. This method also does not suffer from the paradox of anisotropy seen in co-linear arrays (see below).

5.2.2.2 Azimuthal Resistivity Survey (ARS)

This is a very powerful method for measuring in-situ characteristics of fractured rocks. It reveals magnitude and azimuthal variation in the permeability of the bedrock. It has many applications, e.g. in a poorly exposed terrain, where field mapping of fracture system may not be possible. Even in areas of good exposures, extensive field data on fracture characteristic is required for evaluating the anisotropic character of the bedrock. The ARS measures bulk properties of fractured rocks. In such rocks, the parallel geometric arrangement of water-bearing fractures makes the resistivity anisotropic. In this regard, fracture connectivity plays a key role in controlling maximum permeability direction.

The technique utilizes conventional resistivity equipment and is performed by rotating a Wenner array (or Schlumberger array) about a fixed centre point. The apparent resistivity is measured as a function of azimuth, say at 10° or 15° angle interval. The electrode spacing of about 5–25 m is used. When the apparent resistivities in different directions are plotted as radii, an anisotropic figure is generated, called apparent resistivity figure (ARF) (Fig. 5.9). In case of one set of parallel fractures, this is an ellipse.

For a single set of steeply dipping saturated fractures, the true resistivity minimum would be oriented parallel to the fracture strike. However, in this type of azimuthal resistivity survey using co-linear array, the apparent resistivity maximum gets oriented parallel to the fracture strike (Fig. 5.9; also Fig. 5.10a). This is known as paradox of anisotropy and owes its origin to the non-uniform distribution of electrical current density in the direction of fracturing (Cook 2003). It appears to be a result of using current magnitude in the calculation of apparent resistivity, whereas the current density determines the actual differences in potential.

The coefficient of anisotropy of apparent resistivity ellipse is λ $\{=\sqrt{(\rho_y/\rho_x)}\}$. It has been shown that joint porosity ϕ can be approximated under non-shale ideal conditions as $\phi=\{\rho_o\,(\lambda^2-1)/\rho_y\}$, where ρ_o is the groundwater resistivity.

Extending the case of single set fractures to multiple set fractures, it is found that the effect of multiple set fractures is additive in nature. If there are two sets of fractures of unequal development, the azimuthal resistivity plot exhibits peaks of unequal magnitude (Fig. 5.10b). Further, if in an area, joint lengths are less than the electrode spacing and joints are poorly developed, the orientation of the ellipse will be intermediate to the trends of joints and will represent the direction of greatest connectivity. It becomes a function of both

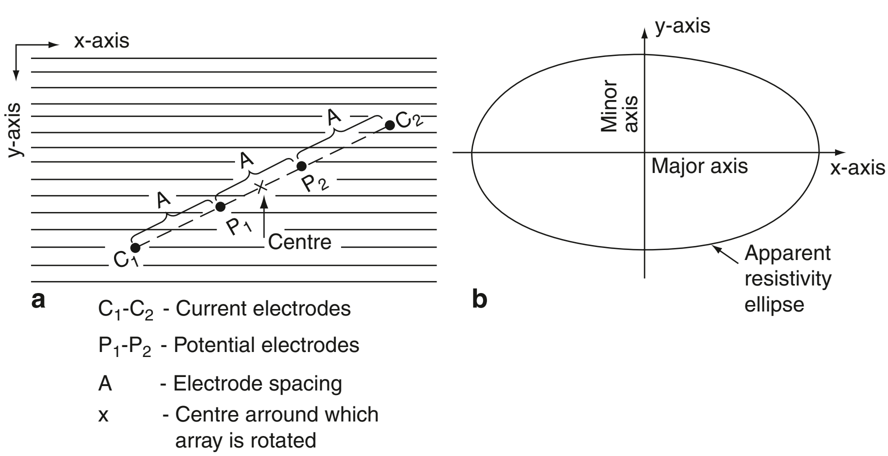

Fig. 5.9 **a** Scheme of a colinear azimuthal resistivity survey and **b** the resulting azimuthal (apparent) resistivity figure (ARF), which is an ellipse in a simple case

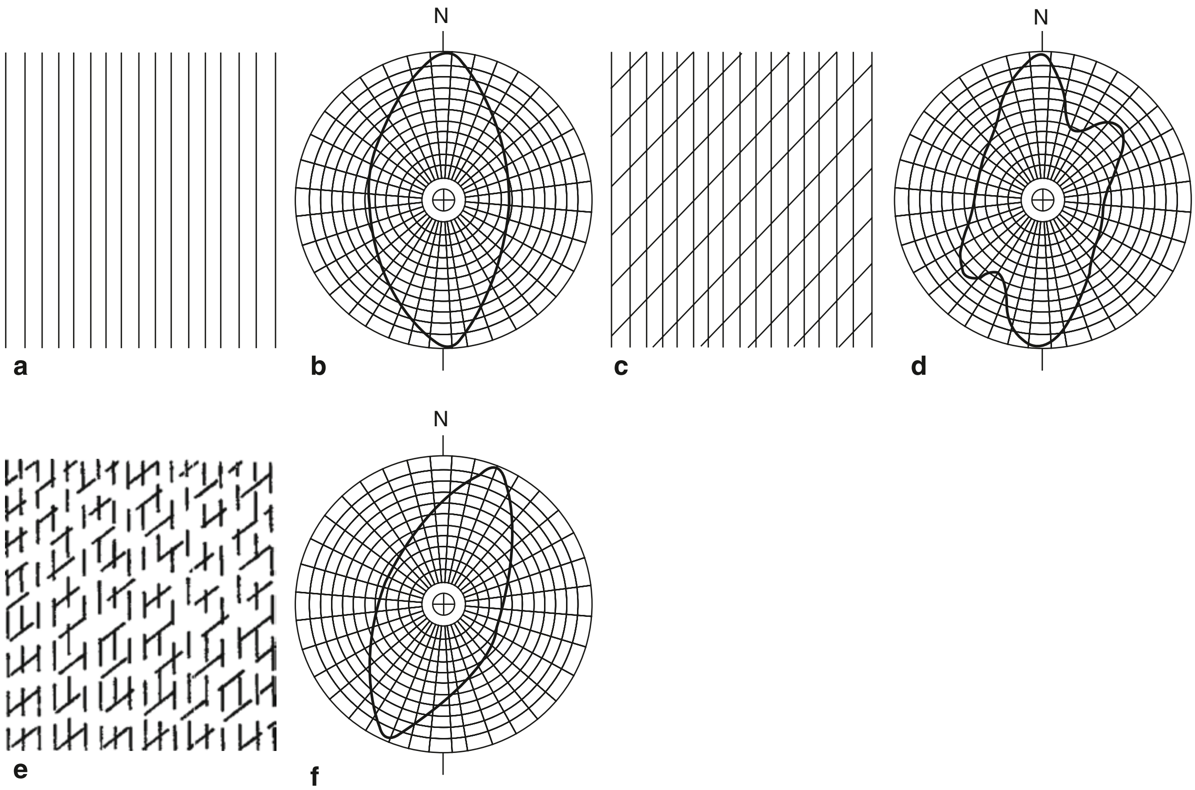

Fig. 5.10 Schematic representation of different configurations of fracture systems and the resulting azimuthal resistivity figures (ARF) using colinear arrays. (Redrawn after Taylor and Fleming 1988), for details see text

average fracture length and fracture frequency of both the joint sets (Fig. 5.10c).

If the spacing of the fractures is large, then different results are obtained at different electrode spacing. Changes in fracture orientation with depth may also lead to different results at different electrode spacing.

Application of azimuthal resistivity survey for detection of fractures has been done by a number of workers, e.g. McDowell (1979), Mallik et al. (1983), Taylor and Fleming (1988), Haeni et al. (1993) and Skjernaa and Jorgensen (1993) in a variety of igneous and metamorphic rocks. Inter-relationship between azimuthal resistivity and anisotropic transmissivity in fractured media has also been shown (Ritzi and Andolsek 1992).

Ideally, the method is valid for homogeneous anisotropic rocks with near-vertical fractures, large fracture length and high fracture frequency, in comparison to the electrode spacing. If the fracture set is not vertical but dips at an angle, the apparent resistivity ellipse has a relatively increased minor axis. For a horizontal set of fractures, it would take the shape of a circle (both axes equal), as horizontal fractures contribute equally to the horizontal permeability in all azimuthal directions.

A close study of the ARF can immensely help in understanding the natural anisotropy in the bedrock. It provides a good representation of permeability anisotropies, which may be difficult to obtain even from field fracture measurements. A narrow ellipse (large-coefficient of anisotropy or large long to short axes ratio) indicates near-vertical continuous parallel fractures, with large aperture. On the other hand, a broad ellipse suggests dipping or less continuous fractures with low aperture. A single peaked ARF indicates one set of fractures (Fig. 5.10a). A double peaked ARF is formed by two sets of fractures, each peak corresponding to one set of fractures (Fig. 5.10b). In some cases the direction of the long axis of the ARF lies in between the strike directions of two major fracture sets, and probably indicates the most conductive path through the fractured rock (Taylor and Flemming 1988).

Before concluding, it may also be mentioned that the azimuthal resistivity method may not be able to distinguish between clay filled and water filled fractures, which have similar electrical properties but greatly different hydraulic conductivities. Such ambiguities are common in geophysical methods.

5.3 Electromagnetic Methods

5.3.1 Introduction

In areas where surface layers are highly resistive, electromagnetic methods may be used with advantage for groundwater exploration. The inductive coupling avoids the need for direct electrical contact, thus eliminating problems associated with resistive dry or rocky surface conditions. Electromagnetic data can also be collected from aeroplanes or helicopters, allowing survey of large areas at relatively low cost.

In case of deeper regolith (say > 20 m), the variation in thickness of weathered zone in an area is important, which can be estimated from EM profile data. On the other hand, in areas of shallow bedrock (regolith < 10 m), fractures in rocks are the target. Lineaments inferred from aerial photography and remote sensing data need to be surveyed by profiling for precise location and potential. In this context, the EM method has assumed the highest utility as an inventory tool. The recommendations from EM survey can then be checked and confirmed by resistivity techniques in more detail, and interpreted with other exploration data.

5.3.2 EM Method—Frequency Domain

The EM method of frequency domain type (often called Slingram) has been the conventional technique for geophysical exploration. The method utilizes a set of transmitter and receiver coils. A sinusoidal current flowing through the primary transmitter coil at a discrete frequency generates the primary magnetic field which induces eddy current in the sub-surface (Fig. 5.11). This current in turn generates the secondary magnetic field which is dependent on the sub-surface conductivity distribution. The induced magnetic field is picked up by the receiver coil and is interpreted to provide subsurface information. The secondary field is very

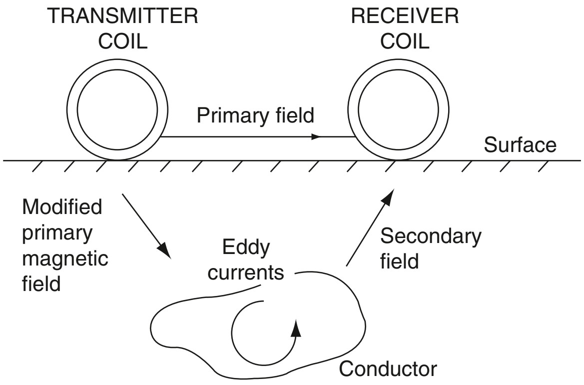

Fig. 5.11 Basic principle of electromagnetic induction prospecting

small in comparison to the primary field and also has a small phase shift with respect to the primary field.

The coil spacing are suitably selected, usually 20/40 m or 50/100 m being more common. The depth of investigation is determined by the intercoil spacing and is conventionally taken to be about one-half of the spacing. A limitation on the depth penetration is provided by the tendency for high frequency energy to propagate close to the surface (skinning effect), so that greater depth penetration is achieved with lower frequencies. The survey is made in a grid such that one axis of the grid is parallel to the main hydraulic conductivity orientation (i.e. rock discontinuity trend). Shorter coil separation and closely spaced EM stations can give better estimates of regolith thickness and dip of the fracture zone.

The EM survey can be carried out in various ways, such as horizontal loop EM (HLEM) (vertical dipole) and vertical loop EM (VLEM) (horizontal dipole). The HLEM is found to be particularly useful for detecting vertical and subvertical fractures (Boeckh 1992). Further, the VLEM system is extremely sensitive to changes in azimuth relative to conductor (fracture) strike. Thus semi-quantitative evaluation of width, depth and strike of fractures zones can be made from the anomaly shapes of both HLEM and VLEM data collectively (Hazell et al. 1992).

A water-bearing fracture acts as a conductor. The vertical dipole EM profile across a vertical conductor is marked by symmetrically placed two apparent conductivity maxima, on either side of a minimum, centred over the conductor (Fig. 5.12a). In case of a dipping conductor, the EM response curve is asymmetrical; the condcutor dips beneath the greater of the two flanking

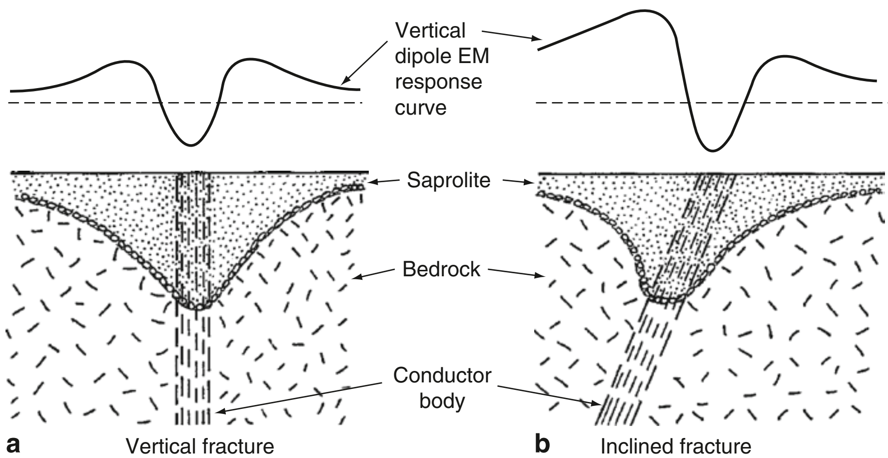

Fig. 5.12 Schematic representation of horizontal loop EM (HLEM) (vertical dipole) response of a profile across a fracture (conductor body) when **a** the fracture is vertical, and **b** the fracture is inclined

maxima (Fig. 5.12b). This anomaly pattern is extremely useful in deciphering dipping fracture zones (Siemon 2006). It can help avoid faulty borehole siting (Wright 1992; Boeckh 1992). Multi-frequency airborne EM method is suitable for shallow subsurface exploration (less than 100 m) and is widely used for groundwater exploration due to its better resolving capabilities. For deeper targets, ground based or airborne time domain EM method is more suitable.

Another important EM method is the one utilising the very low frequency (VLF) band (15–25 kHz) produced by distant powerful radio stations. The VLF-EM field, gets modified in the presence of an electrically conducting body at depth and this change in the field is measured. From this data, apparent resistivity of buried horizon is computed. Although the interpretation of EM-VLF data based on forward modelling is mostly not unique, still it does provide useful information on subsurface conducting bodies. It is particularly useful in areas covered with resistive layers, e.g. dry desertic sands or resistive hard rocks like basalts overlying fractured-weathered water-bearing horizons. For example, Bromley et al. (1994) successfully used VLF-EM technique for detecting fractured water-bearing horizons covered under basaltic rocks in Botswana.

5.3.3 Transient EM Method

The transient (time domain) EM method is a relatively new development, as compared to the conventional frequency domain EM method and other geoelectrical methods. The method requires very sophisticated electronics for measurement and intensive computer processing for data interpretation. The transient electromagnetic method (TEM) has been specially developed for exploration in areas with extensive and thick cover of relatively low resistivity rocks. The conventional frequency domain methods have difficulties in penetrating the top low resistivity cover, and in such cases the TEM is more suited. It can be employed in ground based as well as airborne mode (Christiansen et al. 2006).

All electromagnetic methods are based upon the fact that the primary magnetic field varying in time induces an electrical current in the surrounding ground conductor and generates an associated secondary magnetic field. The information about subsurface geology, i.e. conductivity of the structures and their distribution is contained in the secondary field. However the secondary field is much smaller in magnitude than the primary field. This means that either the measurement is made very accurately or compensation for the primary field is carried out before the measurements. Normally, the primary and secondary fields are measured collectively without any possibility of differentiating between the two.

In the TEM method, the transmitter transmits a pulse and the current is switched off very quickly; the measurements are then made after the primary field has disappeared, i.e. only on the secondary field. It is necessary to measure the secondary field in a sufficient long interval of time. Thus, the TEM method measures the amplitude of a signal as a function of time, and hence the term time domain.

The TEM requires extremely accurate measurements with high precision, quality and spatial density, as the magnitude of variation involved is very small (variation of only 10–15% with respect to background response may be expected in groundwater exploration) and even a small error can make a significant impact on the interpretation.

Advantage of the TEM method is that the depth of investigation is large compared to the loop size. Though the commercial TEM equipments are very expensive, it can be a cost-effective and powerful tool in geologic conditions with top cover of low resistivity rocks, as the data acquisition is extremely fast and large amount of data are collected over a relatively short period of time.

5.4 Combined EM-Resistivity Surveys

Many of the geophysical surveys are run in combination which helps in resolving ambiguities and confirming interpretation from various angles. For example Randall-Roberts (1993) used EM-VLF, VES and SP techniques for hydrogeological exploration in fractured Precambrian gneiss in Mexico. EM-VLF was used to locate and define fractures in plan. VES soundings brought out horizontal sheeting as zones of low resistivity. SP permitted an interpretation of permeable intersections between vertical and horizontal fracturing. Thus, these data sets enabled a three-dimensional analysis from surface geophysical measurements, which was subsequently confirmed by drilling and pumping tests.

Bromley et al. (1994) describe a combination of aero-magnetic, VLF and coaxial EM surveys for groundwater studies in Botswana. In this region, the main aquifer is of Karoo Formation, broken into a series of grabens and horsts structure by several faults and is completely masked under basalts and Kalahari beds. They used low-altitude (20 m height) airborne geophysical surveys to cover 3300 km^2 area. The magnetic and VLF data were used to penetrate the masking cover. The drilling programme was guided by the geophysical data. Highest yields were obtained from fracture zones associated with VLF anomalies and NW–SE set of lineaments.

5.5 Complex Conductivity Measurements

Spatial distribution of electrical parameters of the subsurface media can yield information that can be used to estimate the characteristics of groundwater and aquifer heterogeneity. It can be used to assess the depth water-table, aquifer vulnerability to pollution, aquifer characteristics such as hydraulic conductivity, sorption capacity, dominant flow regime, water content, water movement and water quality.

Complex electrical measurements involve measurements of real and imaginary part of conductivity (Boner 2006). Models have been developed to relate hydraulic conductivity to electrical parameters. The complex conductivity measurements are sensitive to physiochemical mineral water interaction at the grain surface. In contrast to the conventional geoelectrics, a complex conductivity measurement is influenced by textural and mineralogical properties of the aquifer. Therefore it can yield information on hydraulic conductivity (or the sorption capacity) and distribution of contaminants in the pore space.

The electrical conductivity of water-wet porous rocks is mainly related to the properties of pore fluids, pore geometry, and interaction between mineral matrix and pore water. Migration of substances and electric conduction are governed by the geometry of pore network and microstructure of the mineral grain surfaces. The waste disposals or contamination sources can cause changes in aquifer characteristics, in terms of hydraulic pressure, chemical potential or temperature, which can be reflected in complex conductivity measurements.

5.6 Seismic Methods

5.6.1 Basic Concepts and Procedures

The technique is based on the principle that the elastic properties of materials govern seismic wave velocities. In general, a higher elastic modulus implies higher wave velocity in the material. In seismic surveys, waves are artificially generated by an explosion or impact of a sledge hammer, at the ground surface or at a certain depth. The resulting elastic waves are recorded in order of arrival at a series of vibration detectors (geophones), and the data is interpreted to give wave velocities. Seismic waves follow multiple paths from source to receiver. In the near-surface zone, the waves may take a direct path from source to receiver. Further, the waves moving downward into the earth may be reflected and refracted at velocity interfaces. Figure 5.13 shows

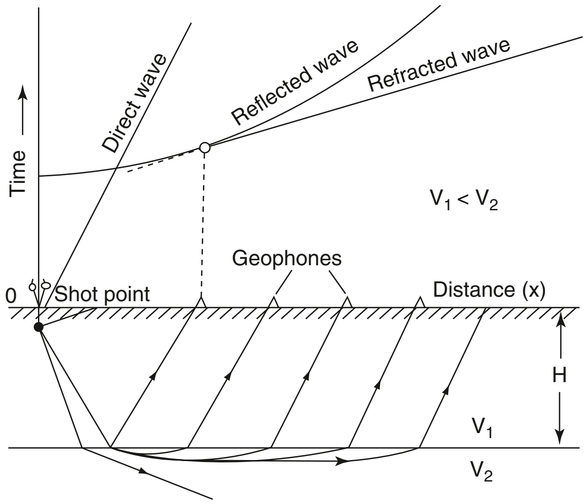

Fig. 5.13 Direct, reflected and refracted waves in a seismic survey

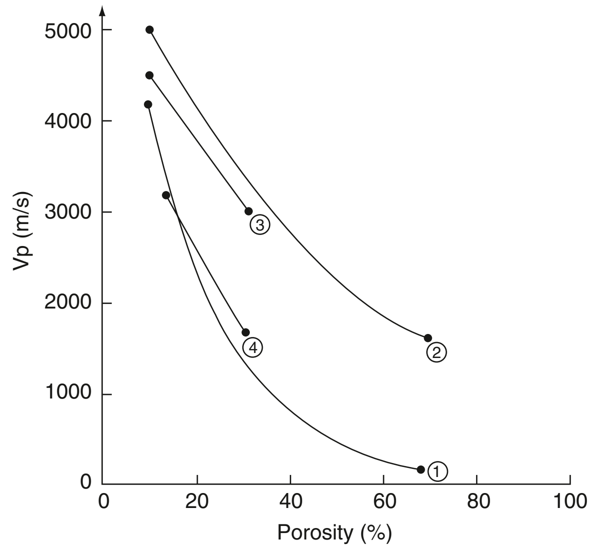

Fig. 5.14 Influence of porosity on P-wave velocity of sandstone. (After Kirsch 2006)

wave travel by direct, refracted and reflected paths. For depth calculations involving two or more layers, various algorithms have been developed. The field procedures for seismic investigations have been made greatly efficient in recent years with the aid of compact, portable computer controlled instruments.

Important rock characters influencing wave velocity are: crystallinity, porosity, cementation, weathering, and discontinuities such as bedding, joints etc. (Rabbel 2006). Massive, compact, crystalline, low-porosity rocks possess higher seismic wave velocities while unconsolidated formations possess lower velocities (Table 5.1). The presence of fractures/porosity in a rock mass causes a reduction in seismic velocity and an increase in attenuation (Fig. 5.14). These effects form the basis for the characterization of fractures by seismic methods. As seismic velocity is influenced by fracturing in rocks, velocities measured in field are much lower than those measured on intact (core) samples in laboratory, for the same rock. Degree of fracturing can be estimated to some extent from a parameter called "velocity ratio", computed as the ratio of the field (in-situ) velocity (V_F) to the laboratory velocity (V_L), in a rock. As the number of fractures decreases, V_F tends to approach V_L. It has been suggested that in general, a velocity ratio (V_F/V_L) of less than 0.5 indicates significantly fractured rock condition. Therefore, the velocity ratio (V_F/V_L) is also sometimes called "fracture index".

Seismic reflection methods are more suited for exploration of deeper structures whereas refraction techniques are more extensively used for investigation of shallower contacts. For groundwater studies, seismic refraction methods are more frequently used, the main application being deciphering the thickness of weathered zone. However, in some cases, optimum use of seismic methods may involve a combination of refraction and reflection principles. P-waves are sensitive to rock porosity and fluid saturation; this makes them a suitable tool for groundwater exploration.

In case the velocity interface is inclined (e.g. dipping strata), it leads to an additional variable. In such cases, recording seismic data in up- and down-dip directions, or reverse profiling is required to obtain true estimates of velocities and depth. The dip of the discontinuity may be calculated by comparing the reverse profile data.

5.6.2 Azimuthal Seismic Refraction Method

Azimuthal seismic refraction method can detect strike direction of major fractures in the bedrock. However, small isolated fractures or fracture zone may not be detected by refraction surveys. A fractured rock mass exhibits anisotropy in wave velocity. For a single set of steeply dipping saturated fractures, a seismic velocity maximum occurs in the direction of the fracture strike and the velocity minimum occurs orthogonal to it.

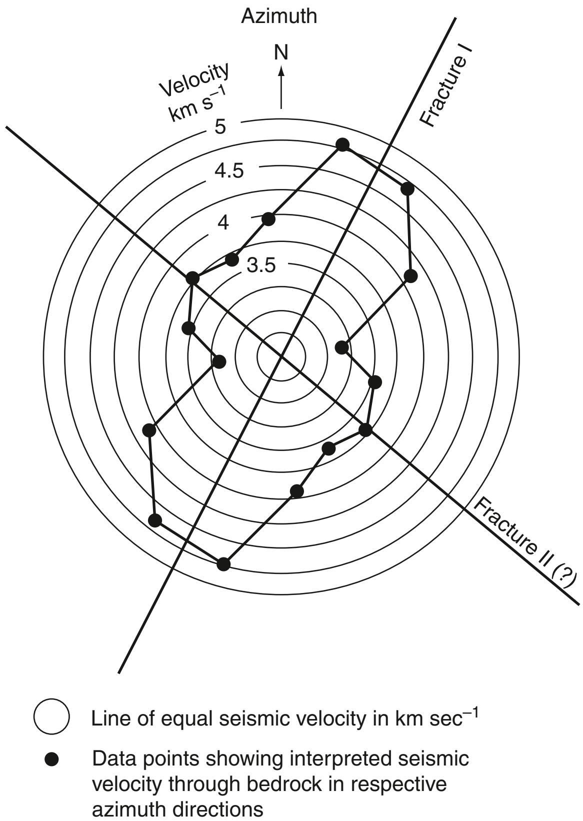

Fig. 5.15 Azimuthal seismic survey indicating the presence of Fracture I and Fracture II (?) at a site in Mirror Lake area, New Hampshire. (After Haeni et al. 1993)

Azimuthal seismic refraction data (using P-wave) can be collected by rotating the survey line at a constant angular increment, about a common centre point. For each survey incidence, a sledge hammer impact may serve as a energy source and geophones are spaced at equal intervals. Data analysis has to be carried out to obtain P-wave velocity for each direction. Figure 5.15 gives an example of the azimuthal plot of seismic velocity data and its interpretation.

5.7 Radon Survey

Radon (^{222}Rn) is an odourless, colourless gas produced by radioactive decay of uranium and thorium in nature. It is the only gas to be radioactive, emitting alpha particles and is therefore, hazardous for health. Its presence and concentration can be detected in water and solid material (soil/rocks) (Ball et al. 1991). Various factors which control radon concentration in groundwater are aquifer mineralogy, fracture characteristics in hard rocks, porosity of sediments and degree of metamorphism (Veeger and Ruderman 1998). A part of the radon generated in nature, may escape in carrier fluids like CO_2 or H_2O through voids and fractures. This property is useful in geothermal and groundwater investigations. Other applications of radon may include delineation of faults, basement structure and possible prediction of earthquake and volcanic activity (Kuo et al. 2006). There is often an increased content of radon in soil-gases over faults and fractured zones, owing to the increased flow of water along these discontinuities. Therefore, Radon survey has been successfully used in some areas for groundwater exploration in basement fractured rocks (Pointet 1989; Wright 1992; Reddy et al. 2006). Further, as the half-life of ^{222}Rn is 3.82 days, it is typically found in higher concentration in groundwater than in surface water. This makes it an ideal tracer for surface water–groundwater interactions such that higher concentrations of ^{222}Rn are expected at places where groundwater is discharging into the stream (Cook et al. 2006).

5.8 Radar Methods

The radar methods can be used from space, aircrafts, ground and boreholes. The radar techniques from aircrafts and space platforms are discussed in Chap. 4. Here we discuss the radar technique from ground (called ground penetrating radar) and boreholes (called borehole radar).

The ground penetrating radar (GPR) is a promising surface geophysical method for hydrogeological studies and has undergone rapid development during the last about two decades (Beres and Haeni 1991; Blindow 2006). It is a method utilizing EM reflection sensing for shallow investigations with high resolution and has found use in groundwater investigations, environmental engineering, and archeological investigations. Its basic principle is quite similar to that of reflection seismic survey with the main difference that in GPR electromagnetic radiation is used where as in seismic surveys elastic waves are used.

The GPR system emits short pulses of radio frequency EM radiation into the sub-surface from a transmitting antenna and the backscattered radiation is

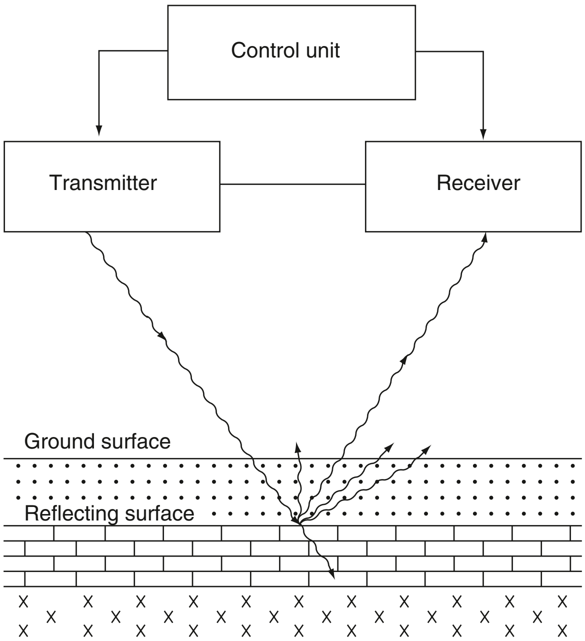

Fig. 5.16 Working principle of ground penetrating radar

sensed by the antenna (Fig. 5.16). The reflected signal is dependent upon the inhomogeneities in electrical properties of the subsurface, such as water content, mineral composition, structure and discontinuities in the rock. The received signal shows the total two-way travel-time for a signal—to pass through the subsurface, get reflected from an inhomogeneity and return to the surface. The GPR system is used in profiles across an area, moving at an average speed of 3–5 km h^{-1}.

Electrical properties mainly electrical permittivity, i.e. dielectric constant and the electrical conductivity are the main physical characteristics of rocks which govern depth of penetration and reflectivity at layer boundaries. Electrical permeability (dielectricity) depends upon the polarization properties of material. It is the dominating factor for the propagation of EM waves in the medium. The speed of EM waves is used for time depth conversion of GPR sections. Typical values of electrical permeability are water = 80, saturated sand = 20–30, air = 1 (Table 5.1). With increasing water saturation, the permittivity systematically increases.

Lower frequencies of EM radiation provide deeper penetration and higher frequencies undergo a skinning effect. However, higher frequencies yield better resolution than lower frequencies. Therefore, a trade-off has to be made with respect to resolution and depth penetration (in terms of frequency). The GPR resolution depends upon the frequency, polarization of the EM wave and contrast in EM properties of the media. The vertical resolution is better in the wet materials than in dry. GPR and seismic reflection have generally not found application in semi-arid and arid areas.

The GPR profiling enables detection of subsurface conductive zones/layers covered by higher resistivity materials. It can be used for estimating depth to groundwater, detecting lenses of perched groundwater, mapping of clay-rich confining bands and monitoring contaminant transport in the vadose zone. This method is also used for mapping buried objects (drums, pipe lines) and abandoned waste disposal sites including hydrocarbon contaminated sites (Domenico and Schwartz 1998; Blindow 2006).

Borehole radar method is quite similar to the surface radar method, except that the survey is carried out in a borehole, and therefore, the transmitter and receiver both are oriented vertically in a borehole. Radar readings are taken at constant intervals as a function of depth. Data are digitally recorded, processed and displayed. From this data, it is possible to interpret presence of important fractures and master joints in the rock (e.g. Olsson et al. 1992; Haeni et al. 1993). In the Mirror Lake site, New Hampshire, USA, a combination of cross-hole hydraulic test data and GPR was found useful for characterizing the fractured rock aquifer in terms of identifying preferential flow paths (Hao et al. 2008).

5.9 Gravity and Magnetic Methods

Gravity and magnetic methods indirectly yield information about favourable structures for groundwater occurrence. These methods make use of natural fields of gravity and geomagnetism (Ernstson 2006). Changes in gravitational and magnetic fields may be observed on the Earth's surface, which could be related to lateral changes in density and magnetic susceptibility of the material at depth. The variation/contrast in density and susceptibility produce small but measurable changes of corresponding fields. The instruments used for these measurements are the gravimeter and the magnetometer. The practical unit for measuring gravity and magnetic fields are milligal and gamma (nanotesla) respectively. In these surveys, the gravity and magnetic values are measured at the pre-fixed observation points in profiles. Various corrections need to be done on the data (e.g. Dobrin 1976). The corrected values of gravity and magnetic field are plotted at the stations/profiles and iso-anomaly map is drawn. Quantitative interpretation is done by analysing the nature of contours, highs and lows.

Across a fault plane, a steep gradient of gravity is observed. Gravity high implies denser rocks closer to the ground surface, e.g., basic intrusions. Lower density materials and cavities produce gravity lows. Gravity methods have a rather coarse resolution, the method being suited for detecting large structures, e.g. regional folds, subsurface domes etc. For the specific purpose of aquifer location e.g. solution cavities in karst areas, microgravity measurements have an interesting potential. Both laterally and vertically extended low density features can also be mapped. The technique requires good knowledge of rock density and their variations, derived from measurements on rock samples.

Magnetic surveys (magnetometry) are among the most cost effective of geophysical techniques for geological mapping. These are quite effective in delineating subsurface mafic dykes, as well as quartz and pegmatite veins, the latter due to diamagnetic property (i.e. negative magnetic susceptibility of quartz). Magnetic surveys can be conducted from space, aerial and ground based platforms. In fact, low-altitude aerial magnetic survey is an extensively used technique in geoexploration.

Magnetic surveys can give an idea of the major geological-structural features. The anticlines would produce positive and synclines negative anomalies. Fault is indicated by a sharp gradient in the magnetic contour map. Since the basement rocks are more magnetic as compared to the overlying sediments, the trend of the magnetic contours is largely related to structural trends in the basement and distribution of basic intrusions. Modelling of magnetic data can bring out highly useful information on structure, dip of faults, contacts etc. This is particularly important as fractured zones along faults and contacts of dykes etc. also form potential aquifer. Orientation of these features can be delineated from magnetic surveys.

Both gravity and magnetic profile data may be portrayed in image mode. This facilitates spatial filtering and image enhancement, which renders image interpretation easy. Figure 5.17 is an example from Botswana, showing the image of aeromagnetic data along with

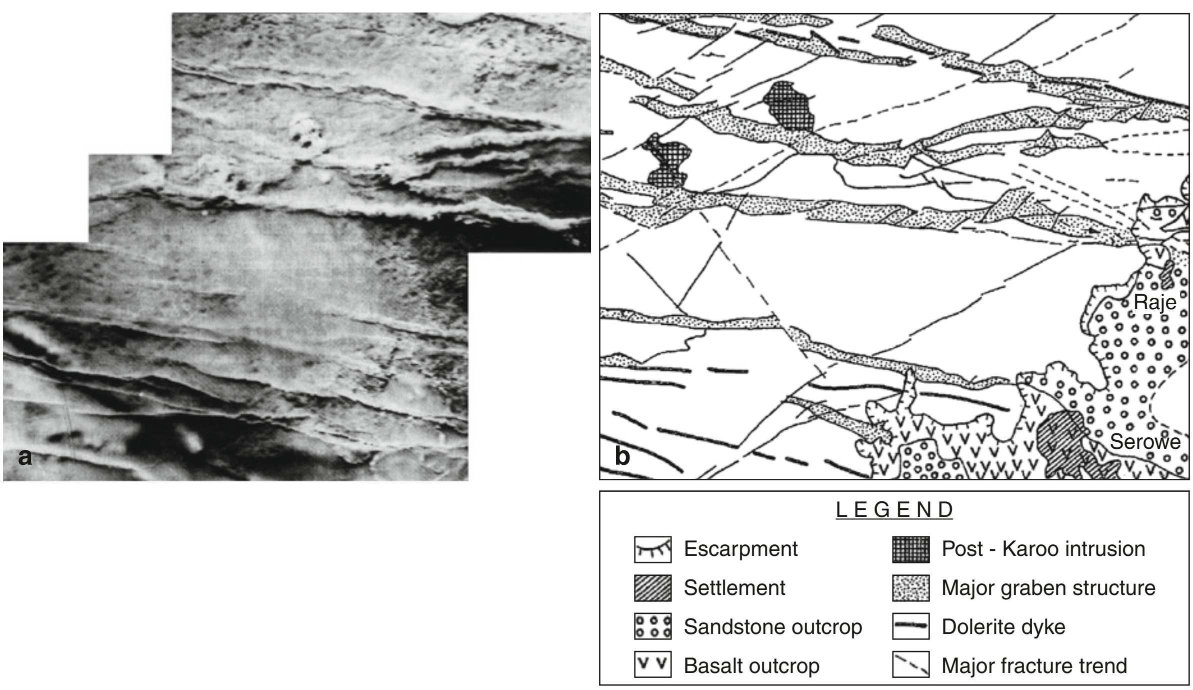

Fig. 5.17 **a** Aeromagnetic residual field image of an area in Botswana and **b** its structural geological interpretation map. (After Bromley et al. 1994, reprinted by permission of 'Ground Water')

an interpretation geologic map. Further discussion on image manipulation—GIS aspects of various geodata sets, to facilitate a coherent integrated interpretation, is discussed under GIS (Chap. 6).

5.10 Magnetic Resonance Sounding (MRS)

Magnetic resonance sounding is a comparatively new non-invasive geophysical method for groundwater investigations. It was first developed in Russia in 1980s by A.G. Semenov and his co-workers and is a specific application of the well known NMR (nuclear magnetic resonance) to groundwater investigations. The nuclear magnetic resonance (NMR) can be observed only in case of specific isotopes of some elements (e.g. hydrogen, carbon, phosphorous etc.) which possess a net nuclear angular momentum and a magnetic quantum number. In the context of groundwater, hydrogen nucleus, which is made of a single proton, is most important as hydrogen nuclei form a major constituent of water molecules. Such a nucleus behaves like a tiny weak magnet and gets aligned with the local (static) magnetic field. An external excitation magnetic field, usually oriented perpendicular to the ambient magnetic field, is used to momentarily displace the average nuclear magnetic moment from the direction of the ambient magnetic field. This leads to precession around the local magnetic field orientation. After excitation, the precessing nuclei will return to their steady state orientation at a rate determined by various 'relaxation factors' and relaxation time forms an important measurement parameter.

The method measures magnetic resonance signal generated directly from protons of hydrogen molecules in groundwater and therefore it has an advantage of direct detection of subsurface water. The depth and thickness of aquifer is estimated by measurements with varied pulse magnitude. The MRS can also be used for estimating porosity and permeability and in predicting the well yields and correlation-interpolation between boreholes. Broadly, it has been found that there is a good correlation between MRS transmissivity estimates and those obtained from borehole pumping tests (Legchenko et al. 2004) (Fig. 5.18). It is particularly useful in fractured and karstic aquifers where there is spatial variation in hydraulic conductivity (Vouillamoz et al. 2003; Roy and Lubczynski 2003; Legchenko et al. 2004). MRS technique is also being used in petroleum industry for estimating porosity and permeability of reservoir rocks. The combined use of MRS and electrical/electromagnetic method provides more reliable information about subsurface geology and water quality. However, the available MRS method has limitations for applications in fractured formations with low effective porosity (<0.5%).

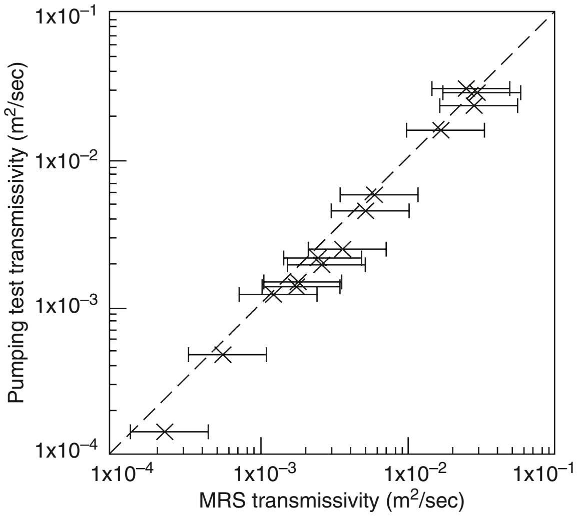

Fig. 5.18 Comparison of transmisivity values derived from MRS and pumping test analysis. (After Legchenko et al. 2004)

5.11 Geophysical Tomography

The advent of Computer Aided Tomography (CAT) has revolutionized medical sciences. Even though similar techniques have been traditionally utilized by seismologists as well as by exploration geophysicists in the field of seismic prospecting for quite sometime, no such special term was coined. But with the emergence of necessary mathematical tools viz., Algebraic Reconstruction Technique (ART), Simultaneous Iterative Reconstruction Technique (SIRT), Back-Projection methods etc, in the field of medical imaging, a new discipline has eventually taken shape in the field of geophysics also, viz. geophysical tomography. Under the umbrella of geophysical tomography, several methods can be included like seismic tomography, electromagnetic tomography, resistivity tomography etc. 'Tomography' simply means a technique used to obtain an image of selected plane of a solid object

(Worthington 1984). It comes from the Greek world '*tome*' meaning a slice.

1. *Seismic travel time tomography*: It basically entails imaging intervening medium between array of receivers and sources. As per geometric configuration of arrangement of sources and receivers, we can have cross–hole, surface–hole and surface–surface travel time tomography. A fracture zone, either air or water filled, in an otherwise massive rock constitutes a low velocity region. Depending upon the orientation of fracture, one among the above modes of seismic imaging can be effective. For example, surface–surface mode is good for horizontal or sub-horizontal fractures whereas near-vertical fractures can be better imaged by cross-hole method, and so on.
   Recently, the cross-hole method of seismic velocity measurement is being more extensively used. It helps in assessing the whole rock mass properties in-situ, between two boreholes. Cross-hole seismic survey is particularly useful in locating cavities or old mine workings in urban areas. Cross-hole seismic measurement underneath the foundations of a building is probably the only effective method to assess the rock mass existing beneath the building. Identification of underground cavities is important to check possible damage to buildings due to subsidence on account of subsurface cavities. In hot dry rock (HDR) systems, cross-hole seismic method is used to delineate cavities created by explosive HDR stimulation. This method is also used for groundwater investigations for mapping fractures (Carruthers et al. 1993). From cross-well seismic investigations in the crystalline rocks near Mirror Lake, Ellefsen et al. (2002) concluded that hydraulic conductivities were higher when P-wave velocity was low ($<5100\,\mathrm{m\,s^{-1}}$), than when it was high ($>5100\,\mathrm{m\,s^{-1}}$), as the fractures increase the hydraulic conductivity and lower the P-wave velocity. This empirical relation helped in preparing a velocity tomogram and thereby creating a map showing zones of high hydraulic conductivity, which was later confirmed from independent hydraulic tests.
2. *EM tomography*: The interest in cross-hole EM tomography is mainly for imaging inter-well electrical conductivity. The sensitivity of electrical conductivity to porosity, fluid type, saturation and temperature has led to the development of cross-well EM systems and imaging algorithms (Rector 1995). Field examples and numerical simulations demonstrate remarkably good resolution of inter-well features when compared to surface EM techniques (Spies and Habashy 1995; Wilt et al. 1995). The cross-well EM tomography can be used to map fractures within highly resistive compact rock (Alumbaugh and Morrison 1993). This method can also track an injected slug of water (Wilt et al. 1995), as conductivity images of data collected before and after injection in a study showed a clear anomaly as a result of salt water plume and indicated the direction of plume migration.
3. *Electrical resistivity tomography* (*ERT*): With the advent of multi-electrode, micro-processor based resistivity measurements (Griffiths and Turnbill 1985), it is now possible to carry out three-dimensional resistivity surveys in a variety of combinations like cross–hole, hole–surface, surface–hole and surface–surface. The methods are being increasingly applied to problems of groundwater flow and pollutant movements, and can as well be used to delineate water filled fractures within moderately resistive host rocks.
   Cross-hole anisotropic electrical and seismic tomograms of fractured metamorphic rock have been obtained at a test site by Herwanger et al. (2004) where they report a strong correlation between electrical resistivity anisotropy and seismic compressional-wave velocity anisotropy apparently related to rock fabric.

5.12 Subsurface Methods

Subsurface methods including exploratory drilling and well logging are essential for confirming results and interpretations made from surface geological and geophysical investigations. Although subsurface investigations are more expensive than surface methods, the precision and reliability of data which they provide more than offset this consideration.

5.12.1 Exploratory Excavation and Drilling

Exploratory excavation may be done by putting pits, trenches, adits and shafts, depending upon the type of problem, topography and needs. The technique provides a means for directly observing and mapping subsurface features, for example, observing how discontinuities continue and behave at depth, and also sampling subsurface rocks. In this stage, various faces and walls need to be very carefully mapped and logged and mutual relationships of various fractures and discontinuities recorded. The excavation methods should be such as to minimally disturb the rock conditions.

However, exploratory excavation being expensive is limited to shallow reaches. For deeper exploration, exploratory drilling is carried out. It helps define the geometry and extent of the aquifer and assessing the groundwater potential. The test holes are preferentially located in such a way that in case of prospects of a good aquifer, the same boreholes can be converted into production wells by redrilling, or reaming to a larger diameter. The test holes also serve as observation wells for monitoring groundwater levels.

The data obtained during drilling is recorded as lithologic log. It is a description of geologic characters of various strata such as lithology, thickness, core recovery etc., encountered during drilling. Drilling time log, consisting of a record of time taken to drill every 2 m of depth is helpful in indicating where there is change of strata or intensity of fracturing and weathering. The rate of penetration of a stratum can be correlated with the formation characteristics and hence with its water-yielding capacity, in a relative manner.

5.12.2 Geophysical Well Logging

Geophysical logs are obtained by lowering a probing tool in a sonde down the borehole. They are used to study the variation of physical properties of subsurface rocks (including fractures etc.) and their fluids. Correlation of logs may reveal the nature of stratification and extension of structures and fractures. The boreholes are logged with a number of geophysical probing tools which provide direct and some quantitative data about the hydraulic characters of subsurface formations.

With the advancement in microelectronics, compact logging units are now available with softwares for interpretation. A number of properties of both formation and interstitial water, such as coefficient of diffusion, formation factor, hydraulic conductivity, specific yield, concentration exponent can be estimated. Further, borehole geophysical data can be used to estimate water properties such as salinity, viscosity and density, and formation properties such as porosity and permeability (Jorgensen 1991).

As far as fracture evaluation is concerned, a large number of logs are required to properly detect and interpret fracture characteristics. Fractured zone produces anomaly with respect to normal or constant hole size. Fractures when open, lead to high permeable paths which can be detected by logging in terms of high drilling rate, loss of drilling fluid, poor core recovery and/or significant increase of borehole size. The treatment here gives a brief resume of the well logging methods with special reference to fractured rocks.

1. *Spontaneous potential log* gives a record of electric potential with depth in the borehole. It is useful for shale vs. sandstone discrimination, but it has limited utility for fracture identification.
2. *Gamma ray log*: Gamma rays are emitted by all natural rock formations as a result of random disintegration of naturally present radioactive elements. The elements producing gamma rays are potassium, uranium and thorium (KUT). The log records total count of gamma rays. The KUT elements naturally concentrate in finer-grained materials (clays, silts) where they are adsorbed in minerals like clays. Therefore, the gamma ray log is regarded as a clay indicator. In fractured igneous and metamorphic rocks, the log response is relatively less consistent. For example, the log may show peak responses due to potassium rich minerals (e.g. feldspars) and/or a clay-rich weathered zone and/or a zone of leaching. Conversely, is some cases a lower activity against the weathered rock may also be observed. Fluid circulation or past fluid circulation in the rock mass can sometimes be also inferred from the gamma ray log. This is due to the presence of uranium oxide which is soluble and highly mobile and can be precipitated in joint and fracture surfaces which form fluid routes within the rock mass. Therefore, gamma logging can identify this local activity where the boreholes intersect such fractures.
3. *Caliper log* measures the diameter of an uncased drill hole as a function of depth. The measurement is obtained with a 3- or 4-arm probe which is electronically opened when the probe is at the bottom of the borehole, and the variation in the borehole diameter is recorded as the probe is winched to the surface. Permeable zones will usually show

a reduction in borehole size due to deposition of thicker mudcake on the borehole. Fractured horizons usually show an increase in the borehole size which may occur due to breaking of the formation wall during drilling. Fracture orientation is likely to affect the borehole ellipticity.

4. *Bore fluid logs* include logging of bore fluid parameters such as electrical conductivity and fluid temperature. Out of these, temperature log has been the most common. Fractured permeable formations are characterised by low temperature anomalies, which occur due to locally increased mud circulation. Logs of fluid temperature and fluid electrical conductivity can be interpreted in terms of groundwater conditions. Fluid logs are run under different hydraulic conditions—usually at rest and also during pumping. A comparison of the two data sets reveals the position where water enters the borehole. These logs are also helpful in investigating inter-aquifer migration of water, adequacy of grouting, quality of groundwater and other related aspects.
5. *Resistivity logs*: An electric log is a record of the apparent resistivity of the subsurface formation with depth. There are numerous variation in the resistivity logs. The electrical logs cannot be run in cased holes and may be operated in dry holes or preferably fluid filled holes. The measured apparent resistivity depends upon the geometric fracture characteristics and the nature of fluid filling the fractures. It is influenced by fracture orientation, size, length, spacing etc.

   The range of resistivity in hard rocks is quite large. Fractures filled with water tend to cause decrease in apparent resistivity in hard rocks. A useful method is by using single point resistance (PR) technique. The PR log represents the varying electrical resistance between a single downhole electrode and a fixed surface electrode. It does not measure the true rock resistivity and is strongly influenced by borehole diameter change. However, unlike multi-electrode resistivity logging devices, its response is symmetrical and bed boundaries are recorded in the correct position, and the relative response is useful for recording the junction between rock units and for correlation. Normal resistivity logs in adjacent vertical boreholes can help in mapping the lateral extension of subhorizontal fractures. Vertical or near vertical fractures may not be detected by induction log due to the fact that the induced current tends to flow in horizontal loops around the borehole and therefore vertical fracture containing conductive fluid, may go undetected in the log. On the other hand, horizontal fractures filled with conducting fluid appear as conductive anomalies.

   Microresistivity logs are likely to miss fractures, as they measure only a small volume of rock around the wellbore. Fractures lead to increased conductivity due to higher local porosity and greater water saturation. Different combinations of laterologs and induction laterologs can be used to decipher presence of fractures close to the wellbore and distant from the wellbore (Van Golf-Racht 1982). However, these advanced techniques are more used in petroleum industry.
6. *Dipmeter log* basically records the dip angle and dip direction of a bedding plane intersecting the borehole. The tool consists of four radial pads positioned at angulary interval of 90°. It is rotated in the borehole at a uniform speed, as it is winched on, yielding four microresistivity curves. The azimuth recording of electrode 1 is continuously made. The dipmeter response may describe all types of discontinuities from horizontal to vertical. Fracture identification log (FIL) is an improved tool for detecting fractures. Higher efficiency in FIL is obtained by superimposing the response of a couple of electrodes, i.e. combination of electrode responses in a specific manner.
7. *Porosity log*: Under porosity logs are included, density, neutron and sonic logs. These logs are capable of detecting fractures and evaluating secondary porosity. In principle, the secondary porosity must be evaluated as the difference between the bulk porosity and the matrix porosity, both of which are measured through logs. A double porosity model is used to link the bulk porosity and the matrix porosity (Sect. 7.2.2). The density log is a gamma–gamma ray log. A gamma ray beam is emitted from an artificial source and a counting system detects the backscattered intensity, which is related to the density of the rock. A higher density causes a relatively lower level of gamma–gamma intensity. Fractures causing higher secondary porosity are indicated by higher gamma–gamma ray count.

   Neutron logs respond primarily to the amount of hydrogen present in the formations. In the case of open, water-filled fractures, neutron logs exhibit anomalies indicating higher porosity. The sonic log is very useful in fracture detection, particularly in dense rocks. It uses a transmitter and a wave receiver. As the transmitter makes an energy emission, different types of shear and compressional waves are generated and received at the receiver. The amplitude, velocity and attenuation of different wave types are influenced by the fracture characteristics. A study of amplitude, attenuation and arrival times of shear and compressional waves can provide indication of fracture orientation and lithology.

8. *Borehole Televiewer* (*BHTV*) is used to detect and evaluate fractures and formation boundaries by direct measurements. It may be treated as a partial substitute for continuum well coring. Combined with drill core data, it is a highly valuable tool. BHTV is carried out in boreholes filled with homogeneous, gas-free liquid such as drilling mud, freshwater etc. BHTV includes a source of acoustic energy and a magnetometer mounted in the tool. The tool is rotated at a uniform speed during logging. The changes in the uniformity of the borehole walls such as fractures, rugs, pits, traces etc. are reflected as changes in picture intensity. It produces a two dimensional image of the borehole. The intersection of fractures with the borehole can also be observed in the BHTV image. The fractures perpendicular to the borehole appear as horizontal traces and those parallel to the borehole appear as vertical traces. Fractures intersecting at angles appear as sinusoids. From these data, the dip and strike of fractures can be calculated. Borehole video camera (BVC) which produces either a colour or a black-and-white image of the borehole, is a cost-effective method to locate fractures, changes in lithology and in-flowing zones, especially in shallow boreholes (depth < 100 m) (Delleur 2007).
9. *Hydrophysical logging*: Hydrophysical logging can identify both vertical and horizontal flows in the borehole, since it surveys the entire length of the borehole rather than providing point measurements. Therefore, it is a valuable method for obtaining profiles of flow characteristics and vertical distribution of permeability (Kresic 2007). *Flowmeter log* is a type of borehole fluid log. It is basically a velocity meter and makes a continuous record of flow profile vs. depth. It provides a confirmation of fracture location. Flowmeter logging during pumping can detect increased velocity of water flow moving to the pump, at various inlet points in the borehole, and is therefore highly useful in detecting water-bearing fracture zones. Packers can be used to isolate portions of the borehole for precise characterisation. Flow-logging tests between boreholes (cross-hole tests) may indicate the degree of connectivity of transmissive zones. Vertical flowmeter logging is practiced to determine vertical flow in a borehole due to differences in hydraulic head between two transmissive units or fractures. Fluid replacement logging is a recently developed technique for identifying the permeable fractures in a borehole. The technique involves replacement of borehole fluid by de-ionized water and subsequent measurement of variations in the electrical conductivity of the fluid in the borehole with time (NRC 1996).

Figure 5.19 shows a suite of well logs from a high-yielding well in Zimbabwe as an example. The

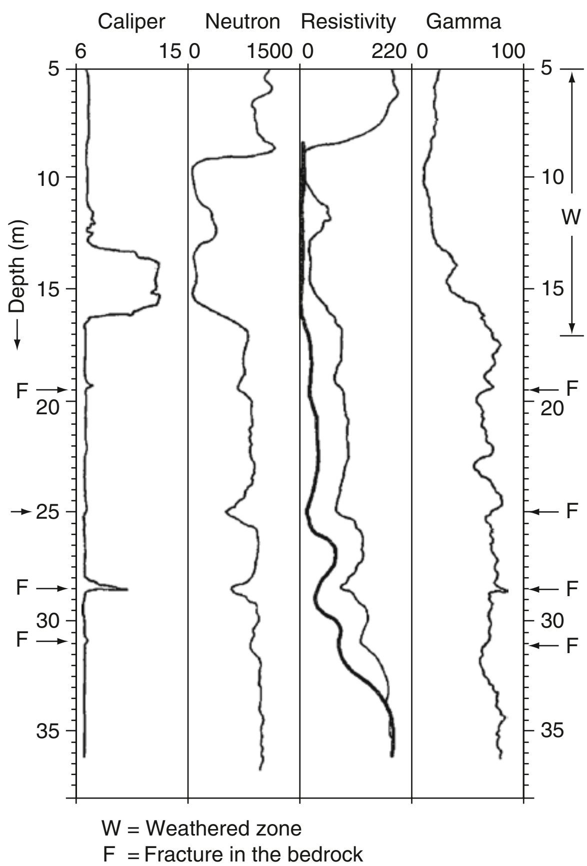

Fig. 5.19 A suite of well logs including calliper log, neutron log and resistivity log from a site in Zimbabwe. The weathered zone extends up to about 17 m depth. Fractures are indicated at 19.5 m, 25 m, 27.5 m and 31 m levels (scales—calliper: inches, neutron: CPS, resistivity: chm meter, gamma: cps). (After Carruthers and Smith 1992)

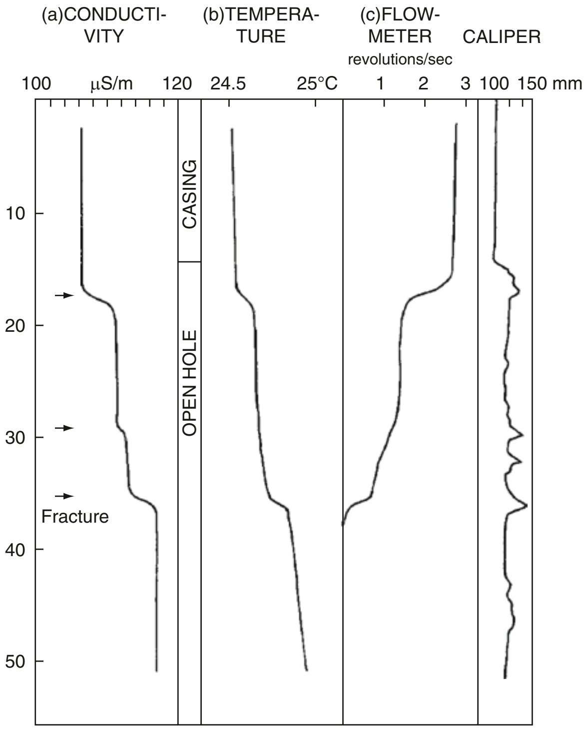

Fig. 5.20 A suite of well logs showing conductivity, temperature, impellor flowmeter and caliper logs in a fractured granite terrain with about 13 m thick weathered rock on the top. The logs were run while the well was being pumped. Note the deflections marking the occurrence of fractures. (After Lloyd 1999)

coincident local excursions in caliper, neutron and resistivity logs mark the individual fractures which provide major inflows to the well. Another example is given by Fig. 5.20 showing conductivity, temperature, flowmeter and caliper logs in a borewell in a granitic terrain. The top 17 m is cased. Fractures are marked by correlated changes in well logs indicating increase in conductivity, temperature and calliper logs.

Summary
Geophysical exploration utilizes the variation in physical properties of rocks such as electrical resistivity, electrical conductivity, density, magnetic susceptibility etc. to differentiate and decipher the various subsurface geologic horizons and their hydrogeological characteristics. Rock anisotropy due to bedding, foliation, fractures leads to anisotropy in geophysical properties. It is essential to integrate geophysical data with field geological and drilling data.
Electrical resistivity surveys have been by far the most popular methods for groundwater studies. Vertical resistivity sounding is used to give depth profile at a place whereas resistivity mapping is carried out for delineating lateral geologic variation. Electromagnetic (EM) methods are particularly useful in areas possessing surface layers of highly resistive nature. In many cases, resistivity and EM surveys are run in an integrated manner. Seismic methods utilize elastic properties of materials. Seismic reflection methods are generally more suited for exploration of deeper horizons whereas seismic refraction techniques are used for shallower depths. In hard rocks, their main application is in delineation of top weathered regoilith zone.
Radon survey is used for detecting fracture and voids etc. and for detecting groundwater discharge into stream. Ground penetrating radar (GPR) has its application in delineating water-table and strata layering/inhomogeneities etc. Magnetic resonance sounding is a relatively new technique to give direct detection of subsurface water. Geophysical tools are also used for logging of drill-wells for subsurface exploration.

Further Reading

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