CHAPTER - 5

GROUND PENETRATING RADAR - INTRODUCTION AND FUNDAMENTALS

During the last decade, the use of geophysical techniques, including GPR, has become popular in many geomorphological studies which rendered it possible to obtain many new and stimulating solutions for geomorphological problems (Schrott and Sass, 2008). The Ground Penetrating Radar (GPR) is an emerging high-resolution geophysical technique used to investigate the subsurface architecture. Ground Penetrating Radar (GPR), sometimes also called as ground probing radar, georadar, subsurface radar or earth sounding radar is a nondestructive geophysical method that produces high quality subsurface data, without digging. The use of GPR technique has tremendously increased in last three decades mainly because of the non-destructive and time dependent nature of the digital technlogy. This technique can provide continuous cross-section profile of subsurface along with the three dimensional pseudo image with accurate depth estimation (Figure 5.1). There are two important non-destructive techniques used to investigate the subsurface. The first uses sound waves which carry information about the different mechanical properties of the subsurface and any buried objects. Two examples of this technique are the high-resolution seismic reflection method and the seismic refraction method. The second technique uses electromagnetic waves and makes use of the electromagnetic properties of the subsurface. The imaging of GPR data is similar to seismic technique because of the resemblance between acoustic and electromagnetic prospecting methods (Davis and Annan, 1989). The important differences are the vectorial character of electromagnetic waves compared to scalar acoustic waves. Another difference is the acquisition setup. A GPR survey is usually carried out with one source and one receiver at a fixed distance and also called as a common-offset measurement whereas, seismic survey needs number of receivers for every source and known as a multi-offset measurement. Generally the seismic techniques are used in oil and gas exploration to obtain an image of the subsurface (100 to 10000 m) by employing sound waves, where as GPR is employed for the study of shallo subsurface typically upto 50m. The seismic reflections are generated when a seismic wave hits a layer in the subsurface with different material properties. In the same way GPR reflections are generated (Figure 5.1) when a pulse hits an object or layer with different electromagnetic characteristics (Davis and Annan, 1989; Daniels, 2000).

GPR is extensively used for subsurface investigations and its demonstrated field of applications are manifold. GPR technique is generally applicable for engineering, geophysical, geological, archeological and other near surface investigations like hydrological and geotechnical inspections. GPR provides realistic image of the near surface features up to the tens of meters in favorable conditions (Figure 5.1).

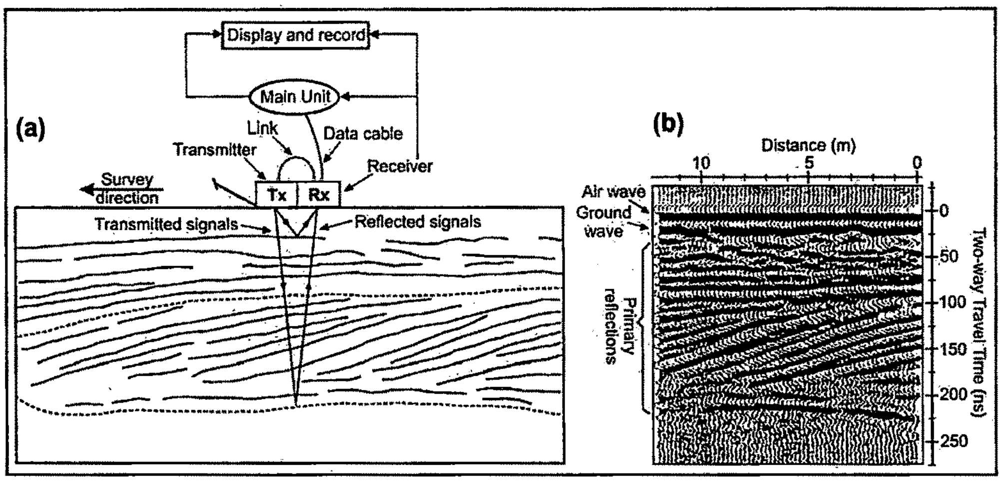

Figure 5.1 Mode of GPR data acquisition and the resulting radar profile in wiggle mode. (A) Diagram showing the GPR system components, manner of signal penetration and internal architecture of the subsurface reflectors. (B) Radar reflection profile in wiggle mode. Position of Ground waves, Air waves and Primary reflections are indicated (after Neal. 2004).

According to Gary R. Olhoeft (www.mines.edu/~golhoeft/), GPR survey was first performed by a group of German geophysicists. After that it was used to measure the thickness of ice and to delineate the fractures. But after that the use of technically corrected promising ground penetrating radar was started in subsurface geological studies. Their system used an improved antenna that gave a better target-to-clutter ratio and was able to more accurately detect important subsurface reflections. With their updated GPR unit, they estimated the location of an underground tunnel, faults, and variation of moisture content in subsurface soils. Now in the internet era varied references exist that cover topics ranging from building GPR units, obtaining data, processing and analyzing. Some technologies have emerged in the past ten years that give GPR users better methods of acquisition, processing and modeling. One of these technologies is the ability to visualize GPR data in three dimensions, with the ability to add time as a fourth dimension. Adding a time component (4D GPR data) to the visualization has allowed scientists to imagine the mobility of the subsurface anomalies.

The purpose of writing this chapter is to appraise the fundamentals of GPR techniques from our own experience and available literature. GPR is now an established, viable technology for probing the shallow subsurface. The research work carried out by author demonstrates the capability of GPR in delineating the shallow subsurface nature and geometry of the active faults. This chapter focuses on the principles of GPR along with some important guidelines for field surveying, data processing and interpretation techniques. The basic aim of this chapter is to provide the fundamentals details about the newly developed GPR technique and to exhibit its eminence in active fault investigations. The various modes of data acquisition, processing and interpretation are described here briefly. Further instrumental details along with rejuvenation of 3D GPR technique, modes of collection and modeling are described in Appendix-I at the end. Radar signal processing, reflection analysis and effects of EM waves scattering are described in view to differentiate original reflection and clutters for reconstruction of radar stratigraphy. Velocity estimation, scientific principles behind the depth penetration and resolution of the GPR data are shown at the later part of this chapter. At the end major geological applications, advantages and limitations of GPR technique are briefly described.

Other geophysical methods, such as seismic methods, borehole and direct sampling methods can be used in conjunction with GPR results to fully characterize the subsurface (Meyers et al, 1996; Maurya et al., 2006). However, the application of GPR in the active fault and palaeoseismological investigations has not been widely used until now. But around the globe many authors have used this technique to investigate the shallow subsurface nature and geometry of the active faults and paleoseismological inspection. Green et al (2003) and Gross et al (2004) have used GPR technique to appreciate the behaviour of active San Andreas Fault (SAF). They have effectively mapped the shallow geometry of this fault using 2D/3D GPR data. According to their findings the GPR is a state-of-art high resolution geophysical technique which can provide onsite results and the correlation of this technique with trenching and drilling data can be very supportive for active fault research.

PRINCIPLES OF GROUND PENETRATING RADAR (GPR)

The shallow subsurface is becoming more important for environmental studies, archaeological investigations and engineering activities. It is important to obtain an image of subsurface to find out the position of buried anomalies and the composition of the subsurface. This information is preferably obtained without disrupting the subsurface, and the technique dedicated to this task is called a non-destructive technique. The GPR is non-invasive technique that utilizes differences in electromagnetic properties of subsurface objects to produce an image of the subsurface (Davis and Annan, 1989). The basic principle and working of the GPR involves the transmission of high frequency electromagnetic waves into the ground, which is reflected back from the sediment interfaces showing variable electrical properties in the subsurface and is received on the surface and displayed in form of a profile (Figure 5.1). The GPR profile shows horizontal survey distance versus vertical two-way travel time in nanoseconds (1 ns = 10^{-9} second). A straight line drawn from the transmitter to the edge of the wave front is called a ray. The interval of time that it takes for the wave to travel from the transmitter antenna to the receiver antenna is simply called the travel time. The recording of both pulses over a period of time with receiver antenna system is called a "trace". The spacing between measurement points is called the trace spacing. The trace is the basic measurement for all time-domain GPR surveys. A scan is a trace where a color scale has been applied to the amplitude values. The round-trip (or two-way) travel time is greater for deep objects than for shallow objects. The EM waves sense the changes in physical properties and composition of the subsurface material like grain size, water moisture, dielectric permittivity and electric conductivity (Davis and Annan, 1989). The radar waves travel downward at a specific velocity that is determined primarily by the permittivity of the material (Jol and Bristow, 2003). The relationship between the velocity of the waves and material properties is the fundamental basis for using GPR to investigate subsurface. The frequency-dependent medium properties can be obtained from a CMP measurement (Van der Kruk and Slob, 1998). The propagation speed (velocity) of the transmitted waves is controlled by electromagnetic properties of the examining objects (Davis and Annan, 1989). The electrical properties of the geological materials are governed primarily by water content, dissolved minerals and expansive clay and heavy minerals which introduce significant changes in the reflection strength of the signals (Topp et al., 1980; Olhoeft, 1984; Beares and Haeni, 1991).

The clayey sediments are normally known to show higher attenuation of radar signal, especially of higher frequencies, thereby affecting penetration as they possess

Table 5.1 Showing typical electric properties of common geological materials (Neal, 2004). Note the relative dielectric permittivity and electromagnetic wave velocity is controlled by water content.

Medium	Relative dielectric Permittivity (E_r)	Electromagnetic wave velocity (m ns^{-1})	Conductivity (mS m^{-1})	Attenuation (dB m^{-1})
Air	1	0.3	0	0
Fresh water	80	0.03	0.5	0.1
Seawater	80	0.01	30,000	1000
Unsaturated sand	2.55-7.5	0.1-0.2	0.01	0.01-0.14
Saturated sand	20-31.6	0.05-0.08	0.1-1	0.03-0.5
Unsaturated sand and gravel	3.5-6.5	0.09-0.13	0.007-0.06	0.01-0.1
Saturated sand gravel	15.5-17.5	0.06	0.7-9	0.03-0.5
Unsaturated silt	2.5-5	0.09-0.12	1-100	1-300
Saturated silt	22-30	0.05-0.07	100	1-300
Unsaturated clay	2.5-5	0.09-0.12	2-20	0.28-300
Saturated clay	15-40	0.05-0.07	20-1000	0.28-300
Unsaturated till	7.4-21.1	0.1-0.12	2.5-10	-
Saturated till	24-34	0.1-0.12	2-5	-
Freshwater peat	57-80	0.03-0.06	<40	0.3
Bedrock	4-6	0.12-0.13	10^{-5}-40	7 X 10^{-6} -24

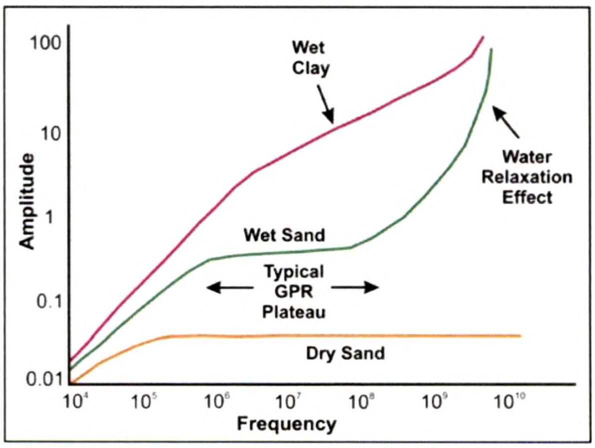

Figure 5.2 Graphs depicting general trends of attenuation of radar signals. Attenuation varies with excitation frequency and material. At low frequencies (<1 Mhz) attenuation is primarily controlled by DC conductivity. At high frequencies (> 1000 Mhz) water is a strong energy absorber. (Based on http://www.geomatrix.co.uk/gprsee.htm).

Table 5.2 Reflection coefficient modeling for typical changes in sediment water content, porosity, lithology and grain shape. The reflection coefficients indicate the proportion of energy theoretically reflected from an interface (Neal, 2004).

Layer 1 Layer 2	Porosity (%)	E_r	Reflection coefficient (+1 to -1)	Geological significance
Dry sand	35	3.1		
Saturated sand	35	20.7	-0.44	Water table
Dry sand	35	3.1		5% porosity change in dry sand
Dry sand	30	3.27	-0.013	
Saturated sand	35	20.7		5% porosity change in saturated sand
Saturated sand	30	17.7	+0.04	
Saturated sand	35	20.7		lithology change to high-porosity peat
Peat	70	46.5	-0.2	
Dry sand	35	3.1		dry heavy-mineral placer deposit
Dry heavy-mineral sand	35	19.9	-0.43	
Saturated sand	35	20.7		saturated heavy-mineral placer deposit
Saturated heavy-mineral sand	35	53	-0.23	
Round grains	33	23.5		
Platey grains	33	16.9	+0.08	grain-shape change
Isotropic grain packing	33	22.5		orientation change for platey grains
Anisotropic grain packing	33	16.9	+0.7	

high water retention capacity and low electrical resistivity (Figure 5.2). However, recent studies have observed increased permittivity in clayey sediments showing variation in grain size, water content and presence of heavy minerals, which results in high dielectric contrast between clay and sand layers enabling detection of sand/clay interfaces (Saarenketo, 1998; Liu and Li, 2001; Carreon-Freyre et al., 2003; Maurya et al., 2006). Small scale textural variations in the subsurface sediments are consequence of change in permittivity and are sufficient to cause reflections of radar signals (Van Dam and Schlager, 2000). The generalized values of electrical properties of some common earth materials (Table 5.1) are present by Neal, (2004). These values of dielectric permittivity control the penetration of radar waves. Higher the dielectric permittivity lowers the penetration of radar signals. Neal (2004) indicated that the changes in the subsurface material will affect the index of refraction, and reflected energy will be produced related to the contrast in the dielectric constant across a boundary between two materials (Table 5.2).

ANTENNA CONFIGURATIONS AND SURVEYING STRATEGIES

There are currently a number of different GPR systems available in the market that are suitable for object oriented subsurface surveying. The present study is carried out using SIR-20 digital radar instrument manufactured by Geophysical Survey Systems Inc. (GSSI), USA with center wave frequencies of 16-200 Mhz (Figure 5.3). All the available systems have slightly different configurations but they are all comprised of five main components; control unit, transmitter, receiver antennas and data storage or display module.

The physical size or dimension of the antenna limits the frequency and wavelength of the transmitted pulse. A high frequency waveform (short wavelength) will provide a more detailed or higher resolution image than a low frequency waveform, but the higher frequencies are attenuated or absorbed at a greater rate (Jol and Bristow, 2003). For any specific GPR application, the appropriate choice of antenna frequency involves a compromise between resolution and the depth of interest. The radiation characteristics and polarization determine the strength of the reflected waves, and become more important as the subsurface complexity increases. Instrument configuration and survey design is determined by the survey objectives and physical factors such as the terrain and site layout-especially the roughness of the

Figure 5.3 The SIR-20 GPR system used in the present study with all necessary accessories manufactured by the Geophysical Survey Systems Inc. (GSSI), USA. (a) 200 Mhz shielded antenna (b) 100 Mhz shielded paired antenna (c) Multi-Low Frequency (MLF) antenna (80-15 Mhz) (d) GPR Main operating unit (e) 12V Battery (power source) (f) Transmitter and receiver units of MLF antenna with transmission cable.

ground surface and the presence of obstructions such as water filled channels, trees, rocks, overhead electrical objects or man-made structures (Jol and Bristow, 2003). Most GPR antennas are easy to handle, and the usual method of operation is to drag the antennas with constant speed across the ground surface in a straight line traverse (Figure 5.3). The receiving antenna continuously records the signals for a finite period of time and the series of single waveforms are combined together to give the influence of mapping layers and objects in the ground. The derived time record or waveform has an early time period corresponding to reflections from shallow targets and later time corresponding to deeper targets, with amplitude representing the strength of the reflection (Neal and Roberts, 2000).

The survey objectives have a significant impact on instrument configuration as well as field layout and selection of appropriate antenna frequency (Figure 5.3). Other factor such as the target size determine line spacing and number of samples required along the traverse line in order to satisfy basic spatial sampling criteria. In practice, GPR measurements can be made by towing the antennas continuously over the ground, or at discreet points along the surface. Both the operations have specific characters and there selection is object oriented. If the transmitter and receiver antennas are separate units, the system is called bistatic antenna (moving mode), where as a shielded arrangement for both the entities is called a monostatic antenna (fixed mode). The bistatic antenna arrangement consists of moving antennas independently to different points and making discreet measurements, while monostatic mode keeps the transmit and receive antennas at a fixed distance and pulling them along the surface by hand or with a vehicle (Figure 5.3). In the moving mode of operation, radar waves are transmitted from a fixed distance and every time it is received and recorded in stacked form. To gain data quality improvement using the low frequency antenna it is recommended that the antenna should be manhandled to each measurement point and kept stationary for the duration of the recording time in order to obtain the best possible result (Jol and Bristow, 2003). GPR operation is digitally controlled from a console (main unit) attached with laptop and another electronic module which connect to the antennas by fibre optic cable. The data is usually recorded in digital format for post-survey processing and display. Distance control along a traverse line are provided by a range of means that include, a well calibrated odometers based survey wheel, accurate positioning of profile length, fiducial marking (manually marking into the data by an electronic push-button during profiling), and differential GPS reading along the transect line.

GPR Penetration depth

GPR can penetrate to a limited depth no matter how the data is processed and visualized. This is true to some extent that the electromagnetic pulses eventually attenuated as dissipate with depth but exploration depth is primarily governed by the material itself and no amount of instrumentation improvement will overcome the fundamental physical limits (Daniels, 2000). Depth to which GPR can image below the surface is dependant on three main factors; the centre frequency of the antenna, the number of interfaces that generate reflections and the dielectric contrast at each interface and the rate at which the signal is attenuated as it travels downward. As the GPR pulse arrives at each interface, a portion of it is returned to the surface and the rest continues into the next layer (Daniels, 2000). As the number of interfaces increase, the proportion of energy that propagates down is reduced. In addition, the greater proportion of energy that is reflected back to the surface at each interface, the less energy that is available to propagate deeper into the ground. This limits the depth of investigation because the reflections of interest get masked by the clutter of the chaotic returns. The conductivity of the investigated material has a major influence on the depth penetration. As the conductivity increases, the material acts more like a conductor than a semi-conductor (Timo Saarenketo, 1998). The frequency used is also important since the resolution of the system and the rate of signal attenuation is proportional to the frequency of the GPR system. With lower frequencies, the wavelength is longer and as a result there is less attenuation due to conductive losses and less scattering from the chaotic reflections by small clutter (Jol, 1995). The main disadvantage of using very low frequencies is that the resolution decreases, such that the thickness of small layers can no longer be measured and small objects are not detected (Jol, 1995). A practical consideration is that, as the frequency decreases, the length of the antenna increases in size and become more difficult to work with. According to Benson (1995) the penetration depth of GPR signals depends on the frequency of the GPR source signal, the antenna radiation efficiency and the electrical properties of the subsurface materials. In a study by Beres and Haeni (1991) to determine applications of GPR for hydrogeological studies, they obtained depths of GPR penetration between 20-70 feet with low-frequency antenna. Greater attenuation of the radar data occurred in areas having saturated sand and clay-based soils whereas more then 90 feet penetration depths were obtained in areas of low electric conductivity (Beres and Haeni, 1991). In conditions where deep ice or salt deposits exist, GPR can penetrate up to kilometers depth (Gergan et al., 1999). The best case observations of depth penetration of GPR in common geological materials are shown in Figure 5.4. By our experience 200 Mhz monostatic GPR antenna attached with odometer based wheel is best to acquire hundreds of meter long and 8-10m deep profile of shallow subsurface for high resolution neotectonic studies.

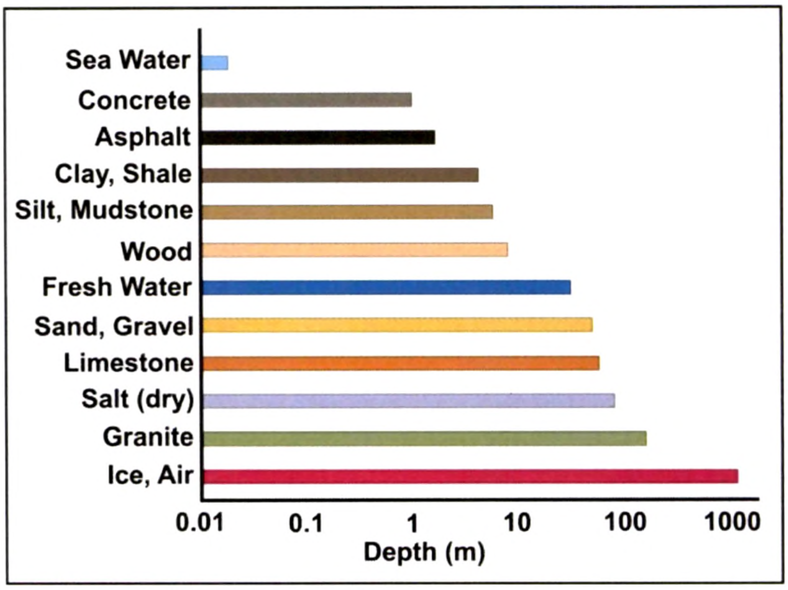

Figure 5.4 The graphical representation of exploration depths in common materials based on "best case" observations (http://www.geomatrix.co.uk/gprsee.htm).

Vertical and lateral resolution

GPR is a high resolution geophysical technique compaired with other geophysical methods for imaging the subsurface, with centimeter scale resolution some times possible. Resolution is controlled by wavelength of the propagating electromagnetic wave in the ground. The vertical resolution depends on the frequency used and the physical properties of the subsurface while the horizontal resolution is a function of the spacing between traces and the footprint of the radar pulse. Vertical resolution of radar profiles has an important implication in subsurface sedimentological studies (Neal, 2004). The precise vertical resolution can be determined by surveying two reflectors that intersect at a gentle angle. However wave theory suggests that the greatest vertical resolution that can be expected is 1/4 of the size of a wavelet (Davis and Annan, 1989). The size of the wavelets that are recorded in a GPR profile is a function of the pulse width of the original transmitted pulse.

There is strong relationship between frequency and wavelength (equation B). Lower the frequency greater the wavelength and higher the frequency shorter the wavelength (Davis and Annan, 1989). If we are looking for small targets at shallower depth higher frequency GPR antenna gives adequate resolution but for larger targets, such as the location of the water table lower frequencies should be used. Selection of the operating frequency for a radar survey should be object oriented. Higher frequencies have shorter wavelengths which yield high resolution while lower frequencies have longer wavelengths that yield greater depth of penetration but lower resolution (Jol, 1995; Jol and Bristow, 2003). There is usually a 'trade off' between spatial resolution, depth of penetration and system portability (Davis and Annan, 1989).

METHODOLOGY

The methodology of GPR technique involves the data acquisition, processing and interpretation. There different methods for obtaining GPR data. The data is recorded on a visual readout or in a digital format (Jol and Bristow, 2003). A brief summary of the methods of acquisition, processing and interpreting GPR data are presented in this section. After a little bit of practice, these techniques can be used in conjunction with other geophysical technique, borehole data and other field data to accurately characterize the shallow subsurface.

Data acquisition

The successful GPR survey depends on the accurate data acquisition parameters, suitable antenna configuration and surveying techniques. The wave energy is lost as the electromagnetic radar signal passes from the transmitting antenna through the subsurface and after certain depth, the signals do not return to the surface. Typically, signal losses are high in soils having high water content and in lake or River surveys (Davis and Annan, 1989). The important basic parameters are the dielectric constant (relative dielectric permittivity) of the investigated area, frequency of the downward radiated radar waves, scanning speed of the antenna and two-way-travel-time (TWT). Higher signal frequencies provide high subsurface resolutions, but only penetrate to shallow depths. Low signal frequencies provide low resolution, but can penetrate up to tens of meter depths (Beres and Haeni, 1991).

The measurements from GPR can be made by two different ways. In continuous manner the shielded monostatic antenna is dragged along a transect line to record a high-resolution continuous cross-section of the subsurface (Figure 5.1). The monostatic antenna contains a pre-fixed unmovable configuration of transmitter and receiver inside a shielded cover, that can be attached with an odometer based survey wheel to determine the horizontal survey distance. In the monostatic GPR survey data can be acquired in two different ways time mode and distance mode. In both the manners GPR antenna is moved along the ground or tow behind a vehicle. The time mode survey comprises the data recording in continuous manner without using the survey wheel. The data recorded in this manner measures vertical and horizontal both the axis in time. But in the distance mode a calibrated survey wheel is attached with antenna to calculate the horizontal survey distance. The data obtained by distance mode shows two-way-travel-time (TWT) in nanosecond and horizontal distance in meter/feet. In both the manners GPR antenna moves along the survey line and the pulses of energy is transmitted through the transmission antenna which is reflected back and recorded by receiving antenna and stored in digital format.

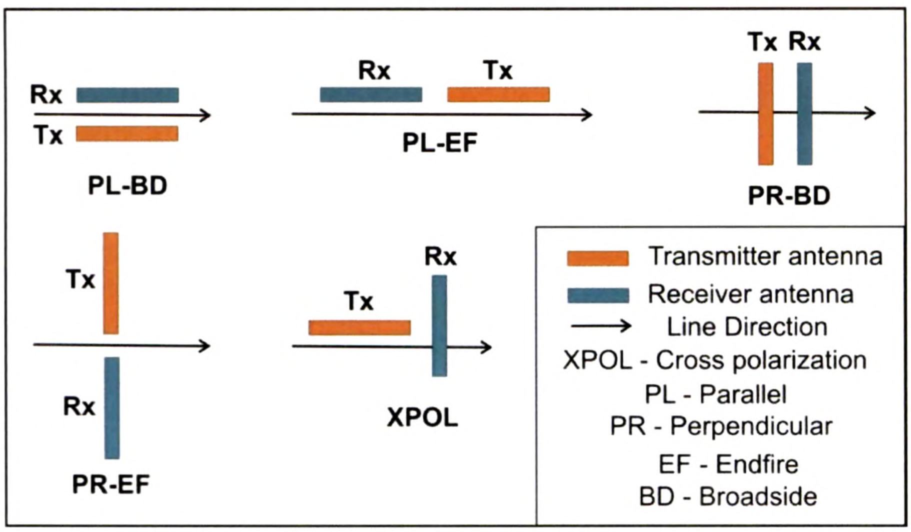

Figure 5.5 Various modes of antenna deployment/orientation for bistatic GPR antenna (Jol and Bristow, 2003). The electric field is assumed to be aligned along the antenna axis.

The second manner comprises a transmitter and receiver as separate entities and the measurements are made by manually shifting the points along the surface. This is known as bistatic antenna configuration (Figure 5.5). The data collection with unshielded bistatic antennas are quite time consuming and gives low resolution images of subsurface compared to monostatic antenna but the center frequency of the bistatic antenna can be changed to achieve greater depth penetration. The fixed-mode (point mode) arrangement has the advantage of flexibility where as the moving-mode (free run) has the advantage of rapid data acquisition (Figure 5.5). Different acquisition set-up can be used to obtain information of the subsurface using multi low-frequencies antennas. Figure 5.5 illustrates the various modes for antenna deployment. For inline orientations, both source and receiver antennas are present on the survey line and the offset between the source and receiver is parallel to the survey line. For the crossline orientations, both source and receiver antennas are not present on the survey line and the offset between the source and receiver is perpendicular to the survey line (Figure 5.5).

The various modes of GPR data collection with bistatic antenna suggested by Huisman et al. (2003) and Neal (2004) are shown in Figure 5.6. According to Jol and Bristow (2003) the cross-pole antenna configuration (bistatic) with orthogonal transmitting and receiving antennas reduced clutter and more effectively focused on the subsurface targets of interest. The data recorded using bistatic antenna can help to calculate the subsurface velocity structure. Some of the important surveying techniques using bistatic antenna are given in Appendix-I.

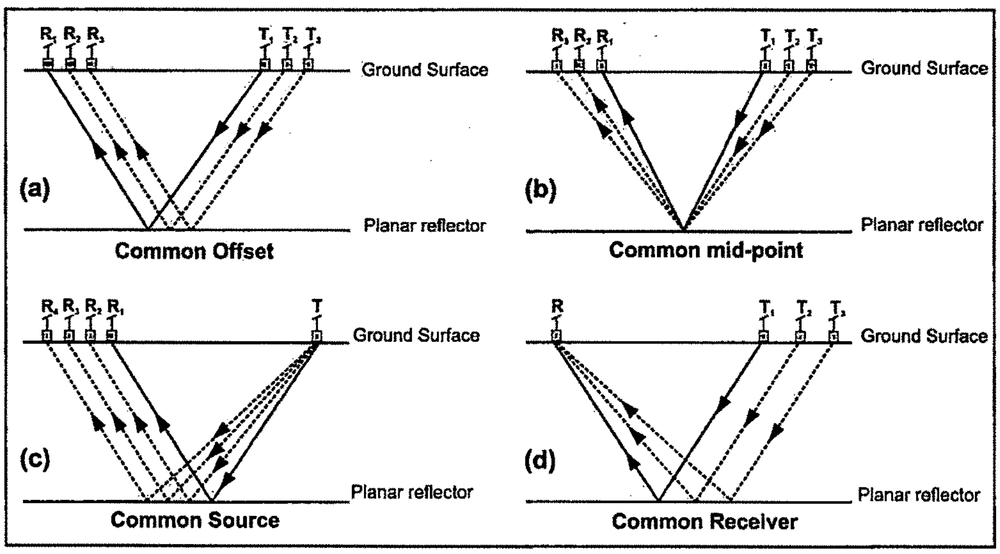

Figure 5.6 Techniques of bistatic GPR survey. T- transmitter, R- receiver. (a) Common Off-Set mode (b) Common Mid-Point (CMP) mode (c) Common Source Mode (d) Common Receiver Mode (after Neal, 2004).

Data processing

After obtaining the GPR data for a particular purpose the next stage comes with many questions like, how is this data processed and interpreted? And what is this data good for? One dimensional trace interpretation is one of the useful ways to analyze GPR data. These days powerful 2D and 3D interpretation softwares are available which can easily discriminate to original reflections from noise. When the GPR unit moves away from the subsurface anomaly signal scattering occurs in form of hyperbolic returns. Appropriate processing is required to remove the unwanted signals from the data, while some GPR data can be left unprocessed (Neal, 2004). The processing and analysis of GPR data needs understanding of fundamentals of geophysics (Yilmaz, 2001). Since the data obtained from GPR surveys is similar to data obtained from seismic reflection surveys, many techniques of seismic data processing can be directly applied to process GPR data (Young et al., 1995; Fisher et al., 1996). These data processing techniques have been developed through years of research and many of them involve complex mathematical equations. In many cases very little processing is required to locate the target of interest. In these cases, the only adjustments that need to be made are to convert the data to a usable digital format, to make gain adjustments to the data, and to determine the depth of each reflector in the subsurface after converting the time. As we know that in GPR technique electromagnetic waves (EM) of specific central frequency is propagated in to the ground by a source antenna (transmitter), where it may interact with subsurface materials in a variety of ways like, attenuation, reflection, refraction and diffraction. The raw GPR data may not show the true subsurface image because of external noises produced by electronic bodies, geometrical inhomogeneity of the subsurface materials, concrete structures, metallic bodies and many other things. To reduce the clutters in GPR data care should be taken during data acquisition (Jol and Bristow, 2003). The representative field maps of survey design should be prepared to identify the cluttered signals in post survey data processing and interpretation. At present many sophisticated geophysical softwares have been developed by various commercial organizations to process large amount of 2D and 3D GPR data which allow almost any imaginable manipulations (Annan, 1999). The flow chart of GPR data processing is shown in Figure 5.7. Before starting the GPR data processing, one should make backup of raw data to avoid any inconvenience. First of all, the header

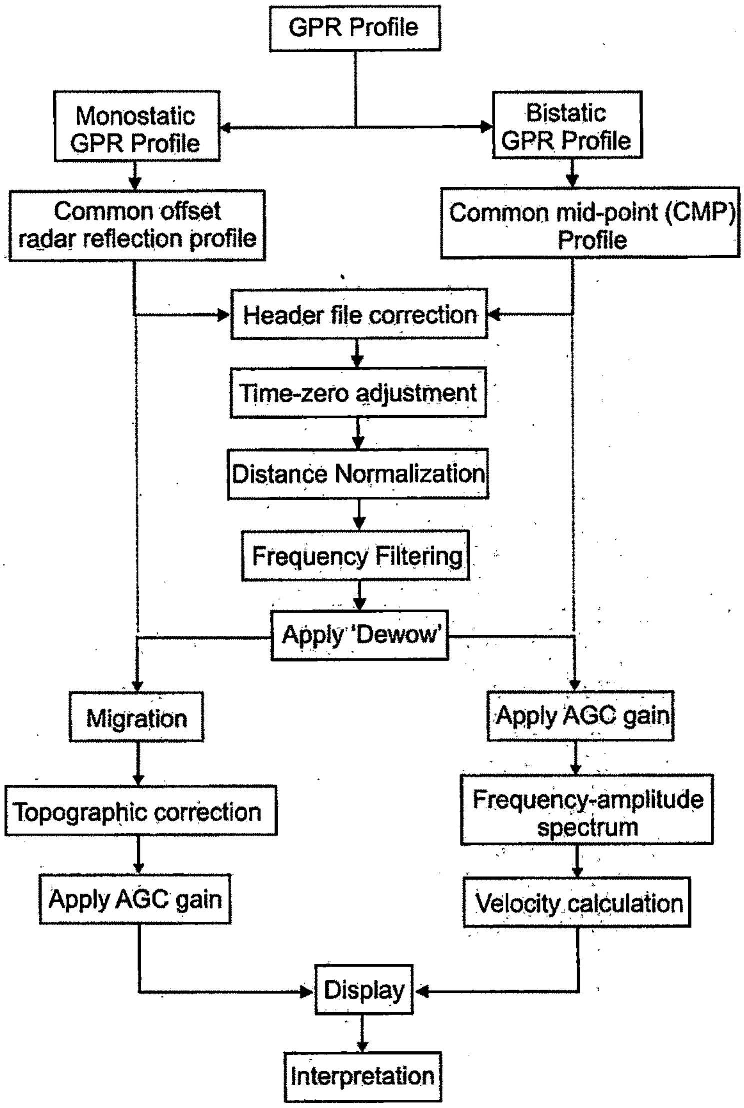

Figure 5.7 Flow chart showing the general GPR data processing sequence for monostatic and bistatic antennas.

file parameters are edited using field notes, which contain the information about the data collection parameters, range of time window, scanning and sampling speed and some background information. This is basic but an important step of successful GPR survey. Systematic information regarding profiling to be maintained includes, survey direction, elevation details, survey grid layout and physical and electrical properties of the medium (Jol and Bristow, 2003). Many times background inFormation is required for appropriate parameter selection for radar data processing and interpretation and for future reference also. The next is to apply the time-zero correction for shifting the traces along the time axis (ns) to correct the misalignment of the first break in radar profile (Neal, 2004). It is important for accurate depth estimation for subsurface reflections. Similarly, the distance normalization operation (Figure 5.7) is applied to reduce the difference of antenna towing speed and to get accuracy of horizontal scale for GPR profile (RADAN for Windows, 2000). This operation calculates the number of scans between every horizontal meter and then equally divides them throughout the distance to get actual scanning speed of the receiver. It is an important processing step for measuring the accurate position of the buried anomalies along the distance axis. Some GPR profiles collected in adverse conditions require special processing. Some of the GPR data processing steps are described in appendix part.

Velocity analysis: It is an important step of GPR data processing and interpretation. Velocity analysis involves determining the propagation speed of the radar waves in the subsurface materials, then converting the reflection travel times into the depths. This is most easily done using methods described by Benson (1995). Generally, the velocity of the upper surface sediments can be determined by straight forward process of drilling, digging or outcrops logging. But the velocity determination of the subsurface layers using radar data sets is a sophisticated and non-destructive technique which provides vivid digital view of subsurface velocity structure. In free space, electromagnetic energy travels at the speed of light (0.3mns^{-1}). In the subsurface it travels at a fraction of the speed of light, usually in the range 0.01-0.16mns^{-1} (Table 5.1). The propagation velocity can be determined in three ways: common-mid point (CMP) velocity survey, point-source reflection analysis and direct water depth measurements or core depth logging. The first two methods are generally more effective for determining velocities of the upper surface geological layers. The data acquired by common-mid point (CMP) method gives more direct image of the subsurface velocity structure and are commonly used to determine the subsurface discontinuities. This method gives more accurate results for depths of subsurface reflectors and is adequate for most analysis. Profiling technique for CMP method has been described in appendix. The velocity of the electromagnetic waves can be determined from equation A, where as the signal wavelength can be calculated from equation B: described by Benson (1995).

$$v = \frac{c}{\sqrt{E_r}} \quad \text{. . . . . (A)}$$

Where:

v = The velocity of the wave through the subsurface material.

c = The speed of light (30 cm/nanosecond).

E_r = The relative dielectric constant.

$$\lambda = \frac{v}{f} \quad \text{. . . . . (B)}$$

Where:

λ = Wavelength.

v = The velocity of the wave through the subsurface material.

f = Frequency.

The electromagnetic waves are very sensitive with small scale textural and chemical changes. Presence of moisture in subsurface sediments strongly controls the penetration of radar waves. In the equation A, the relative dielectric constant is only unknown factor. The relative dielectric constant of soil can be measured in the laboratory by comparing the capacitance of capacitors encased with air and soil. As shown in Table 5.1, water has highest dielectric permeability as compare to other geological material. Note that the dielectric constant of the water is 80 and the other geological materials ranges between 4 to15. These large differences in dielectric values explain why the radar wave velocity strongly depends on the water content and affect the depth of penetration in common geological materials (Figure 5.4). The velocity increases at frequencies greater then 1000 Mhz because of the relaxation of the water molecules (Davis and Annan, 1989). The attenuation of radar signals increases rapidly at frequency above 100 Mhz (Figure 5.2). The attenuation of radar signals are also occurs when the heterogeneous subsurface medium are scanned by higher frequencies.

Time-depth conversion: To determine the accurate depth of any subsurface reflector, velocity of the profiled sediments must be known. The dielectric and conductivity properties of the profiled sediments controls to penetration speed (velocity) and attenuation of the radar signals (Davis and Annan, 1989). The velocity and the attenuation are two main things that describe the propagation of high frequency radio waves in the ground. The attenuation decreases as the frequency decreases in wet geological material (Davis and Annan, 1989). The two-way-travel-time is converted into the depth by direct on-site calibration of the radar antenna over an object of known depth, or by conducting a common-mid point stack with bistatic antennas. If the direct measurements are not practical, GPR velocities are estimated using "typical" soil dielectric values and propagation velocities from similar sites. According to Benson (1995) the depth of subsurface reflector can be determined by the equation given below.

$$d_r = \frac{vt_r}{2} \quad \text{. . . . . (C)}$$

Where:

d_r = The depth to the reflector.

v = The velocity of the wave through the subsurface material.

t_r = The two-way travel time to the reflector (taken from the GPR trace).

All the radar data do not require similar kind of processing algorithms. It is based on the accuracy of data sets and subsurface conditions. Processing of GPR data involves modification in raw data, so that it is more easily visualized and interpreted but the selection of processing parameters should be based on the physical modeling and theoretical background of the geophysics not on the users whims (Jol and Bristow, 2003).

Data interpretation

The interpretation of GPR data is the most ambiguous part of this modern geophysical technique (Yilmaz, 2001). It is based on the characterization of specific signal patterns received from the subsurface anomalies. The processed GPR data provides a closely approximate image of the subsurface. Identification of origin of reflections is important prior to GPR data processing and interpretation, whether they are the true reflections or clutters from external objects (Jol and Bristow, 2003). Awareness about the factors that contribute to the electrical properties of the sediments is necessary. It is also advantageous for the interpreter to be aware with field conditions, survey strategies and aims of the interpretation. Some times raw GPR data does not represent the real image of the subsurface due to diffraction of radar energy from complex buried structures, which appear in profile as a random or multiple reflections and may require some special processing steps (Annan, 1999; Daniels, 2000). Every specific reflection pattern represent to any particular subsurface structures. In seismic stratigraphy the reflection profiles are subdivided into seismic sequences by surface of discontinuity (Yilmaz, 2001). The principles of radar stratigraphic interpretation are derived from the seismic interpretation methodologies and much of the terminologies associated with seismic stratigraphy can be directly applied to GPR interpretation (Jol and Smith, 1991; Neal, 2004).

The radar stratigraphy is a powerful technique for the systematic description of reflection generated by primary depositional structures and other subsurface anomalies. Variation in the reflection patterns due to amount of water and clay content are displayed by changing the reflection strength of the amplitude in GPR profiles (Carreon-Freyre et al., 2003). Presence of water strongly affect to radar returns, because the pores of unconsolidated sediments having water content shows higher dielectric constant than air filled sediments (Ekes and Hickin, 2001; Sridhar and Patidar, 2005). It is an important criterion to demarcate the lithological boundaries and stratigraphic interfaces in the sediments having contrasting electromagnetic properties.

The GPR data collected to interpret the tectonic structures may be complicated in some cases and one can easily misinterpret the data (Young et al., 1990; Bano et al., 2000). In such cases one should correlate the data at every processing stage to characterize the original reflections. Interpretation of fault plane/zone in GPR profile is a challenging task and requires some special processing steps like, Migration and Deconvolution along with some relevant basic information about the orientation of surface and subsurface features and survey layout (Gross et al., 2004). Generally, every GPR profiles shows two high amplitude near horizontal reflections at the top with high velocity and low attenuation, represent the position of direct air and ground waves. These are preliminary but important reflections of GPR profile, which some times used to decide the processing and interpretation strategies. The thickness, position and strength of first ground return (ground wave) reveals important information about the upper surface and survey conditions. These reflections illustrate highest amplitude strength in GPR profile without any fluctuation. The fluctuation in the ground waves along the time axis may reveal important information about the changes in dielectric permittivity of the upper surface layers (Bano et al., 2000). The arrival time of direct ground waves is a function of ground surface propagation velocity (Kruk and Slob, 2004). The interpretation of GPR data should be object oriented because sometime much interference are incorporated with the data, which can not be removed in processing. If the user applies over filtering to clean the data then original reflections may also be wipeout. In general the subsurface is three dimensional and the downward radiated radar waves travel into the subsurface as a circular form, which can be reflectd by structure outside the plane of the transect line (Neal, 2004).

The important reflection patterns that appear in radar profile should be critically evaluated like; thickness and intensity variations of the reflected signals, changes in the dip of the reflections, termination or displacement of the reflections along a plane, reductions in amplitude strength, presence of diffraction hyperbolas, frequency variation along the vertical trace and many other complementary reflection patterns. The GPR data can be analyzed in many different ways depend on the aims of the interpretation. Mainly the GPR data can be displayed in three different modes; one dimensional trace, two dimensional cross section and three dimensional display (Figure 5.8). The one dimensional trace represent to a gather carried out at particular shoot along the vertical time axis (Figure 5.8a). The two dimensional cross section is sequential array of number of traces along the time axis represent lateral continuity of the anomalies (Figure 5.8b). A three dimensional display is fundamentally, a block view of GPR traces recorded at different positions along the surface (Figure 5.8c). Normally a 3D block is constructed by interpolation of parallel closely spaced 2D lines. The 3D visualization softwares allow viewing the data from many different angles that helps to understand the internal architecture of study area (Figure 5.8d). The amplitude-contouring function can create the elevation model from the time slice, based on reflection strength at the particular depth (Patidar et al., 2006).

Definition of radar stratigraphy allows subsequent environment interpretation, particularly when combined with ground penetrating radar or other forms of suitable data. The integration of GPR data interpretation with borehole logs and other geophysical methods can be used to accurately characterize the subsurface. According

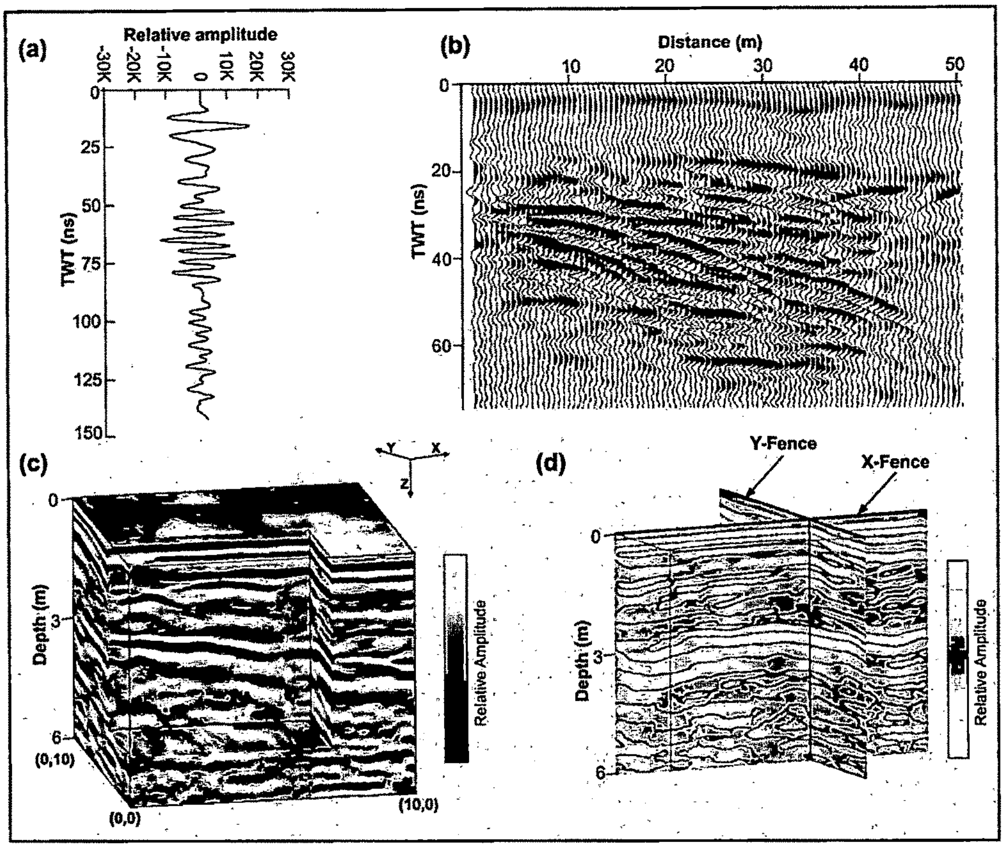

Figure 5.8 Different modes of display of GPR data. (a) One dimensional trace (b) Two dimensional cross section (c) Three dimensional block view and (d) Three dimensional data in slice mode.

to Neal (2004) migrated radar profiles are normally much more suitable for full radar-stratigraphic interpretation because they provide a more coherent and realistic image of the subsurface. These days many advanced geophysical processing packages are available to perform variety of migrations, 3D modeling and interpretation of GPR data.

ADVANTAGES AND LIMITATIONS OF THEGPR

GPR is one of the important tools, ideally suited for obtaining realistic high resolution subsurface image up to the 50m, which is marked as a blind zone in seismic data. The instrument is compact and easy to handle compared to the logistic requirement of other geophysical survey instruments, hence can be easily transported and operated in far off places. There is no need for digging electrodes for measuring subsurface reflections by GPR. The radar signal penetration is site specific, determined by the dielectric properties of the soil or man-made objects such as asphalt, concrete, and the conductivity of the subsurface materials. GPR signals propagate well in sand and gravel because of their physical properties and low electrical conductivity but the conductive soil such as clay cause attenuation and loss of target resolution (Carreon-Freyre et al., 2003). The GPR can detect small structures, palaeoliquefaction features from the contrast between dielectric permittivity of sand and clay which is not possible by any other geophysical technique (Maurya et al., 2006). The radiation pattern of radar waves from the transmitter is cone-shaped, approximately 15 degrees to the antenna dipoles in circular form. Therefore, buried objects may be detected before the antenna is located directly over them and GPR anomalies may appear larger than actual target dimensions. Buried utilities, metal objects, drums and metal scraps, underground cobbles, bricks, concrete structures and land mines appear as high-amplitude hyperbolic reflections on the radar record (Young et al., 1990; RADAN for Windows, 2000).

Obtaining data along multiple survey traverses or along 3D grid can help in determining the size, shape, and continuity of buried objects (Young et al., 1990; Bano et al., 2000). For instance, buried utilities may be interpreted from hyperbolic reflections and signal disparity. Some times due to subjectiveness of GPR data interpretation, confirmation is required by trenching and drilling. But the errors in analysis of borehole logs, incorrect radar velocity estimations, poor GPR resolution, interference between GPR reflectors, and other factors can give poor correlation between GPR characterization and borehole logs. The monostatic antenna gathers data at much faster rate then bistatic antenna, but some times terrain conditions can be restrictive. The multi low-frequency (MLF) bistatic antennas can penetrate deeper but the size of the assembled antenna do not allow for profiling around dense vegetation. The high frequency (<100 mhz) GPR systems allows penetration up to 10-15 m, therefore ideal for neotectonic and palaeoseismic studies where shallow depth but high-resolution images are required. The recent advancement towards wireless 3D GPR technology can open new avenues for high resolution shallow subsurface studies. The integration of Global Positioning System (GPS) and Geographical Information System (GIS) with GPR technology can solve several technical limitations of this method and make new avenue for near surface research (Baozheng et al., 2004).

The main disadvantages of the GPR technology are as follows:

- The equipment (hardware and softwares) is relatively expensive.
- In the areas having significant structural relief, data may be contaminated by echoes and multiple reflections and can create confusion for processor and interpreter.
- Presence of water and clayey minerals have strong influence on GPR depth penetration.
- This tool is futile when water depths exceed 30 feet but in saline waters it does not work.
- The field data does not provide any direct depth information.

For the most part, GPR is a fast, non-destructive and eco-friendly method to characterize shallow subsurface and is a state-of-the-art geophysical technique to provide successful explanations for many geological applications.

GEOLOGICAL APPLICATIONS OF THE GPR

These days GPR is extensively used to image the subsurface because its demonstrated field of applications are manifold. It has been used in neotectonic, palaeoseismic and sedimentological studies in different parts of the world. It is also an acceptable method to image the thickness and fractures of the ice sheets, permafrost soil research and sedimentological studies (Jol and Smith, 1991; Van Overmeeren, 1998; Neal, 2004; Shukla et al., 2008). Radar facies and sequences have been recognized and linked directly to sedimentological characteristics seen in cores and trenches (Beres and Haeni, 1991; Gawthrope et al., 1993; Sridhar and Patidar, 2005; Shukla et al., 2008). GPR studies carried out by Bridge et al. (1998) revealed more insitu details particularly in delineating the lithofacies, geometry, and orientation of large scale inclined strata sets associated with channel bar migration and channel filling. Lui et al. (1998) studied the ground water flow pattern in fractured crystalline bedrock. Annan et al. (1991) and Daniels et al. (1995) observed the distribution and migration of subsurface liquid contaminants. GPR surveys and study have been carried out on alluvial fan sediments to characterize reflection patterns and to assess the potential of GPR in these deposits (Ekes, 2001). GPR studies have been conducted to detect Quaternary deformations, near surface active faults in unconsolidated sediments, palaeoliquifaction studies and earthquake subsidence events (Cai et al., 1996; Meyers et al., 1996; Busby et al., 1999; Bano et al., 2000; Gross et al., 2000; Lui and Li, 2001; Maurya et al., 2005, 2006; Bhatt et al., 2006; Mulchandani et al., 2007; Patidar et al., 2006, 2007, 2008). Depth of water table and sedimentary facies which correspond to bars and channels are imaged by GPR which bring insight into recent fault activity (Bano et al., 2000; Shukla et al., 2008). GPR studies have been helpful in identifying sand blow features induced by historic earthquakes in shallow sedimentary deposits and to delineate the subsurface pattern and palaeoseismic facies in active areas (Chow et al., 2001). It has been useful to delineate upward fault termination, colluvial wedges and sand injection, unconformities, reverse faults, fault related fold, thus all indicating palaeoseismic activity. The GPR is therefore ideally suited for detecting and imaging subsurface geological features up to the depth of several tens of meters and to construct a complete picture of subsurface features left by earthquakes and other tectonic events.