CHAPTER – 6

GROUND PENETRATING RADAR STUDIES ALONG KATROL HILL FAULT

High resolution shallow subsurface mapping of tectonically active areas is vital for understanding future seismic risk. To understand the behaviour of active faults in recent past, accurate mapping of fault plane/zones is of fundamental importance for future palaeoseismological investigations (Green et al., 2003; Salvi et al., 2003). Geomorphic characterization of tectonic landforms provides structural history and a first-order classification of excavation localities. In the paleoseismology the fault excavation studies are common and reliable technique. But the identification of adequate trenching sites can be difficult where faults are buried or have been eroded since their last motion. The inimitable sets of geologic events and conditions are required to record and conserve evidence of neotectonic activities. Some times the deformational features lie below the surface or rapidly masked by younger geomorphic events. Delineating structural and stratigraphic relationships in the shallow subsurface prior to excavation requires qualitative geophysical exploration. GPR is capable of producing high-resolution images of near surface ranging from a few meters to tens of meters in depth (Davis and Annan, 1989). GPR is an emerging geophysical technique to explore shallow subsurface geology. It is analogous to seismic reflection methods, in creating a vertical cross-section of reflector geometry and amplitude. GPR is particularly advantageous for high resolution mapping of subsurface structures, and can thus image fault-offset layers or fault planes themselves (Cai et al., 1996). It can therefore be applied to determine the subsurface stratigraphy and tectonic landforms or features produced by coseismic deformation (Cai et al., 1996; Anderson et al., 2003).

IMPORTANCE OF GPR TECHNIQUE IN FAULT STUDIES

GPR technique has been proved to be a powerful tool in fault studies around the globe. Faulted geological horizons are good radar reflectors. It is conceivable that a high angle fault could generate a diffraction which is more commonly produced by other discontinuities (Beres and Haeni, 1991; Sun and Young, 1995). If the lithologies change across the thrust plane, a change in reflection pattern may occur, this can be mapped as distinct radar facies (Jol and Smith, 1991). It may also be possible to identify repeating patterns of reflections if thrusting has repeatedly stacked a geological sequence, which produces a number of distinct radar reflections (Busby and Merritt, 1999). The GPR techniques can be used as an important reconnaissance tool to assist selection of sites for geological excavations, and consequently, it may be helpful in accelerating the construction of the paleoseismological chronology. The geological trenching and excavation can only go to a depth of limited distance but the GPR is nondestructive time dependent technology.

Many authors from all around the globe have used GPR for mapping the Quaternary deformation and to delineate the young faults. GPR data has been found extremely useful for precisely locating and investigating near surface characteristics of faults in Quaternary sediments (Cai et al., 1996; Wyatt and Temples, 1996; Salvi et al., 2003; Ferry et al., 2004; Patidar et al., 2006, 2007). GPR has been successfully used to map the active faults in different geological settings (Meschede et al., 1997; Liner and Liner, 1997; Bano et al., 2000; Gross et al., 2002, 2004; Rashed et al., 2003). Busby and Merritt (1999) identified a thrust faulting in young sediments on the basis of truncation and offsetting of reflections in GPR profile. GPR studies were carried out to delineate the sub-surface pattern and palaeoseismic facies of the active Chihshang Fault, a segment of the Longitudinal Valley Fault, Eastern Taiwan by Chow et al. (2001). A reverse fault is also characterized in GPR profile on the basis of offsetting of the multiple stratigraphic units. According to their interpretation most of the reflecting horizons are planar but some deformation in the soft sediments of footwall, adjacent to the fault surface is marked due to dragging of the fault. Ground Penetrating Radar studies have been carried out on the Quaternary deposits of west Cumbria, U.K. to investigate the deformation structures in the sediments (Busby and Merritt, 1999).

The GPR survey conducted in the New Madrid seismic zone in the central USA by Liu and Li (2001) indicate, the application of this technique to understand the paleoliquifection features and their causes. The similar kind of work is also carried out in Kachchh, western India by Maurya et al. (2006). This study was based on liquefaction craters produced by a hazardous 2001 Bhuj earthquake. They have correlated the features shown by GPR data and the ground truth of paleoliquefaction revealed by geological excavation. GPR has been successfully used to recognize the active fault strands and their behaviour with young Quaternary sediments (Bano et al., 2000). The recent movements along the fault and subsurface deformation pattern can reveal immeasurable information regarding the stress regime and the nature of the fault. Gross et al (2002, 2004) used high frequency GPR systems to create three-dimensional view of subsurface to understand the nature of San Andreas Fault (SAF) and Wellington fault. Patidar et al. (2006, 2007, 2008) have also used GPR profiles to appreciate the nature and behaviour of Katrol Hill Fault. According to their findings the selection of paleoseismic sites in dynamic, range-front environments like KHF can be difficult, because of rapid erosion and poor preservation of coarse-grained, channelized alluvium. The most obvious tectonic landforms, range-front scarps, are often too old to constrain sequences of specific rupture events. The faulted deposits that do provide paleoseismic ages, however, are often eroded or buried by younger geological events. In those cases the subsurface images of stratigraphic and structural relationships at multiple sites are useful prior to excavation and the same idea is applied in present study.

GPR STUDIES ALONG KHF

The rugged landscape of Katrol Hill Range reveals imprints of multicyclic tectonic movements along E-W trending Katrol Hill Fault (KHF). The origin and subsequent tectonic history shows that KHF is seismogenic and have been active throughout the Quaternary period. Delineation and characterization of shallow subsurface nature of associated active faults is essential for appreciating neotectonic activity and the prevailing stress regime in the area. The detailed GPR studies were carried out along KHF, an important intra-basinal fault of the southern Mainland Kachchh to understand its nature, potential for stress accumulation and to delineate the neotectonic and palaeoseismic activity (Figure 6.1). In the present study, GPR was used to image the geometry of the fault planes and stratigraphic framework, where surface evidence of faulting is inconclusive. This fault has an important role in Quaternary landscape evolution of the southern Mainland Kachchh. Various phases of neotectonic activities are marked along this fault suggest its reactivation throughout the Quaternary period (Thakkar at al., 2006; Patidar et al., 2007, 2008). Details of tectonic geomorphology and Quaternary sediments and their neotectonic implications have been described in chapter 3 and 4. The geomorphic setting of KHF is characterized by a complex interplay between deposition, erosion, and deformation, due in part to the uplifted mountain front and wide back-valleys. These attributes make this as a unique study of characterizing the nature and behaviour of active faults in dynamic geomorphic environments. Nature and orientation of faults significantly

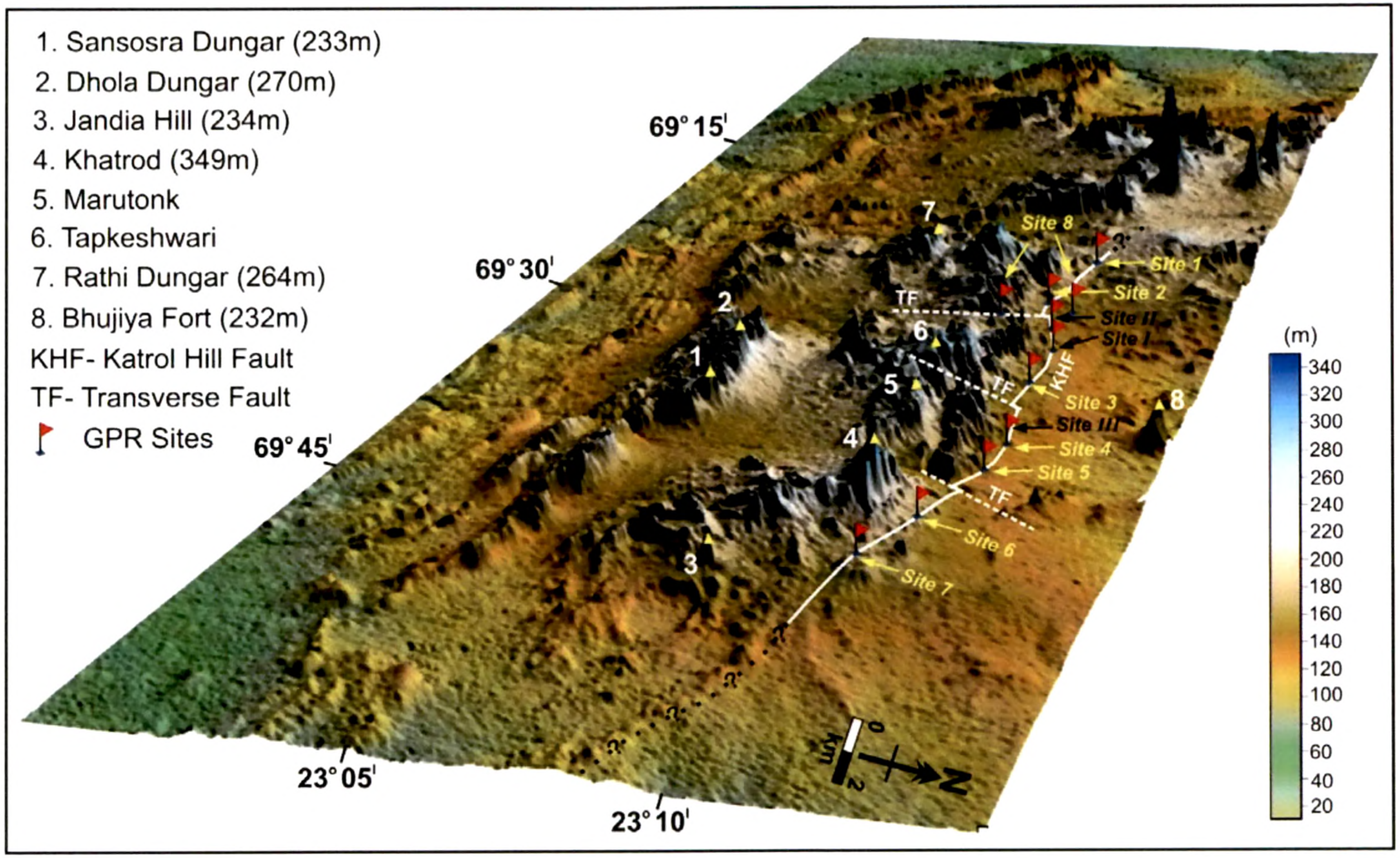

Figure 6.1 Digital elevation model (DEM) of the study area. Location of the Katrol Hill Fault (KHF) and transverse faults are based on present field and GPR studies. The locations of the GPR survey sites are also marked.

influence neotectonic and seismic activity (Ganas et al. (2004). Comprehensive GPR surveys were carried out to understand the nature of KHF in recent past and its effects on Quaternary sediments (Figure 6.1). The upgraded SIR-20 GPR system with high frequency (40-200 Mhz) antennas manufactured by Geophysical survey system Inc (GSSI) was used during this investigation. In the absence of subsurface mapping, the KHF is generally marked at the base of scarp however, the present study has been able to precisely delineate the location of the fault plane and its nature in the shallow subsurface. 3D GPR data provides a vivid view of subsurface fault geometry and internal architecture of the fault zone.

DATA ACQUISITION AND PROCESSING STRATEGY

Ground Penetrating Radar is the most suitable geophysical technique to produce the high resolution image of the shallow subsurface. The previous chapter describes basic fundamentals and principles of the GPR technique. The profiles from Katrol Hill Range were obtained by sheilded 200 Mhz, 100 Mhz and Multi-low frequency (MLF) antennas. Data generation by GPR involves moving the antennas or shifting it manually in point manner over predetermined and measured transects while the profiles are displayed and stored on laptop computer which controls the main GPR unit as well (Jol and Bristow, 2003). Each of the sites was narrowed down after attempting several unsuccessful surveys starting from the base of the scarp, gradually moving away towards north until the fault was picked up in the profile. As it is the usual practice and requirement of the GPR surveys, the process was repeated several times until good quality data were obtained. Several long transects were taken up by GPR at these sites with a view to precisely locate the fault plane/zone. The GPR profiles were obtained by manually towing the antenna along measured survey lines across the fault trace inferred from our geomorphic mapping. At the preliminary stage of surveying, several trial profiles were raised to determine the basic acquisition parameter and a set of most appropriate parameters were applied to obtain final GPR profiles. The time window of 140-150 ns, auto gain function with 5 points and the sampling rate of 512 sample/scan were found adequate for 200 Mhz frequency monostatic antenna. Three dimensional GPR survey was also carried out to visualize the internal architecture and deformation pattern of the Katrol Hill Fault plane/zone. 3D GPR data was collected using 10X10 m grid with 1 m offset between transect line.

The time window of 110 ns was selected for 3D acquisition. The best data sets were subjected to post-survey processing using sophisticated Geophysical softwares (RADAN, 3D Quick Draw and Super 3D). The general sequence of processing followed is shown in Figure 5.7. The file header parameters were edited to correct the horizontal scale and surface positions of the reflectors. The Distance normalization function was applied on all the profiles to establish constant horizontal scale. The power spectrum was calculated to select the filter values and then the vertical and horizontal filters were used to remove interference (noise) produced by extraneous objects. The identification of the unwanted signals and causes of their origin is difficult but an important step of GPR data processing and interpretation (Neal, 2004). Some times the interpretation of tectonic induces features in GPR data is difficult due to diffraction of electromagnetic energy (Young et al., 1995). AGC (automatic gain control) was applied on some profiles to enhance the visibility of low frequency features. Surface normalization was applied to profiles those were obtained over undulating surfaces. The multiple offset reflection profiles (CMP) were also collected from the study area and the calculated velocity of 0.12m/ns was used for time-depth conversion (Figure 6.2).

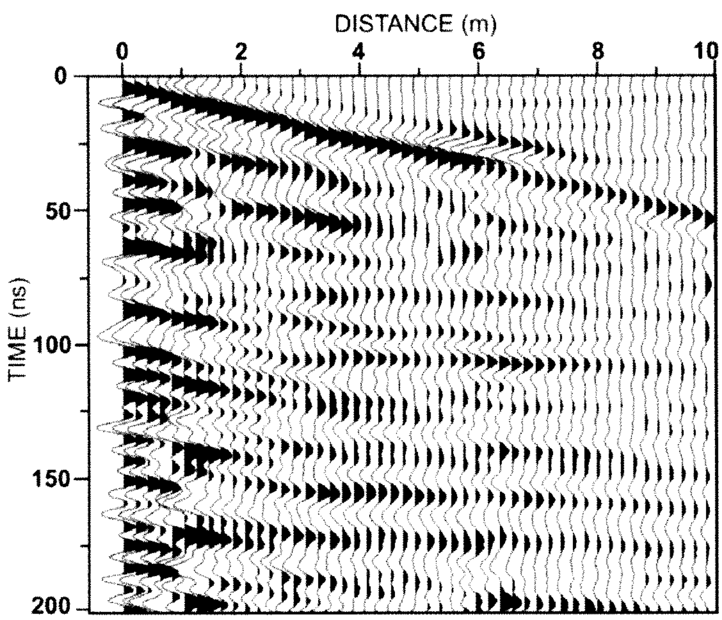

Figure 6.2 Representative Common mid-point GPR profile collected using 40 Mhz bistatic GPR antenna to determine the subsurface velocity structure of the study area.

CRITERIA FOR RECOGNISING FAULT IN GPR PROFILES

The basic principles of seismic data processing and interpretation are used in GPR data interpretation (Davis and Annan, 1989). The interpretation of faults in seismic profiles is based on apparent offsetting of stratigraphic reflections rather than direct reflections from fault whereas in GPR profiles the direct reflections from fault plane are observed (Cai et al., 1996; Slater et al., 2003). Recognition of radar facies is an important step in the interpretation of GPR data. A radar facies is defined as a group of reflections or reflectors whose parameters differ from adjacent units and usually define lithological units, sediment packages or mappable three-dimensional sedimentary units (Bristow, 1995; Jol and Bristow, 2003; Maurya et al., 2006). Reflection terminations and offsetting in GPR data is direct indicators of faulting. However, faults demarcating contrasting lithologies are easier to interpret as they show distinct radar facies owing to strong dielectric contrasts. Sediments produced by faulting are characterised by a diffuse radar pattern (Meschede et al., 1997). Criteria commonly applied for locating faults on the GPR profiles are; the termination of laterally continuous reflections along a plane, presence of diffraction hyperbolas around the fault plane, drastic decrease of amplitude along the fault plane and the offsetting of reflections from either side of the fault strand with varying intensities and the changes in dip angle and the thickness of reflected signals across the fault plane. The above discussed criteria have been used to interpret the GPR profiles obtained during the present study.

All GPR profiles show two near horizontal continuous reflections at the top that is due to highest amplitude strength of radar waves. The first return is the result of high velocity (at near the speed of light ~ 0.3 m/ns) and low attenuation of radar energy in air which is marked as direct air waves. The next return is the direct ground waves which travel directly from the transmitter to the receiver through the top skin of the ground. As the KHF separates two lithologies having different textural characteristics are also reflected in radar reflection pattern (Maurya et al., 2005; Patidar et al., 2006, 2007, 2008). The shale rich lithologies to the south of the fault, in general, produced thin reflections with high amount of diffraction whereas the sand rich lithologies of the northern part show homogenous reflections with little amount of diffraction. The comprehensive description of all the GPR survey sites (Figure 6.1) along the KHF is shown in next section.

GPR STUDY SITES

In the present study, the GPR survey was carried out at selected sites along Katrol Hill Range to characterize the shallow subsurface nature of the KHF to provide evidence for the type of stress conditions responsible for differential uplift and ongoing seismic activities. With the help of satellite image interpretation, DEM modelling and detailed field investigations the sites were selected to perform GPR operations (Figure 6.1). Since the KHF trends in E-W direction, all the GPR surveys were carried out along the N-S oriented transects located at the different segments of the KHF with a view to precisely locate the fault plane/zone and to determine the near surface characteristics of the fault. Total no of 10 GPR survey sites covering the Katrol Hill Range and presented in this thesis (Figure 6.1). Eight sites are described in this chapter while the remaining two are presented in the next chapter.

Velocity analysis

To obtain accurate results and right interpretations, velocity analysis was performed using 40 Mhz Multi low-frequency (MLF) antenna. The calculated velocity values are used to convert two-way travel time into depth. The obtained values are applied on each GPR profiles, to calculate accurate depth of subsurface anomalies. The aim of the velocity estimations is obtain the minimise error in the final interpretations of the GPR profiles. The velocity analysis was carried out using Common mid-point (CMP) method. Several profiles were collected from different parts of the study area. The velocity profiles were collected from every GPR survey locations using CMP method. A representative CMP profile is presented in Figure 6.2. The profile was obtained using 40 Mhz bistatic GPR antenna. The initial offset distance was fixed on 1.5 m, while the transmitter and receiver were shifted in opposite directions by 20 cm step size up to the maximum distance. The final data was collected with two-way travel time window of 200ns. The detailed methodology of CMP data acquisition is described in Appendix-I. The relative dielectric permitivity of 6.5 was found adequate for the sand rich lithologies of the study area (Table 5.1). The frequency analysis was also performed in order to obtain the loss factor and to check the filtering effects of the ground in the radar signals. Although the antennae used was a 40 Mhz center frequency and the values of the center frequency of the spectrum amplitudes from the radar data are nearly 20 Mhz or lower. The average velocity of the medium is calculated from the equation A given in chapter 5. Values obtained by the analysis of the CMP profiles at all locations were found to be similar because of similar lithological characteristics all along the KHF. The velocity values of the formations occurring on either sides of the KHF were also comparable owing similarity of the gross lithologies. The average velocity of 0.12 m/ns is used to interpret the GPR profiles obtained during the present study.

Site 1: GPR survey near Desalpar

This profile was taken across N-S transect to the south of Deshalpar (Figure 6.1). This profile was obtained on undulating ground which was subjected to corrections during post-survey processing by applying Surface normalization (Figure 6.3). The profile shows a part (50 m) of the GPR data obtained by a 200 Mhz antenna

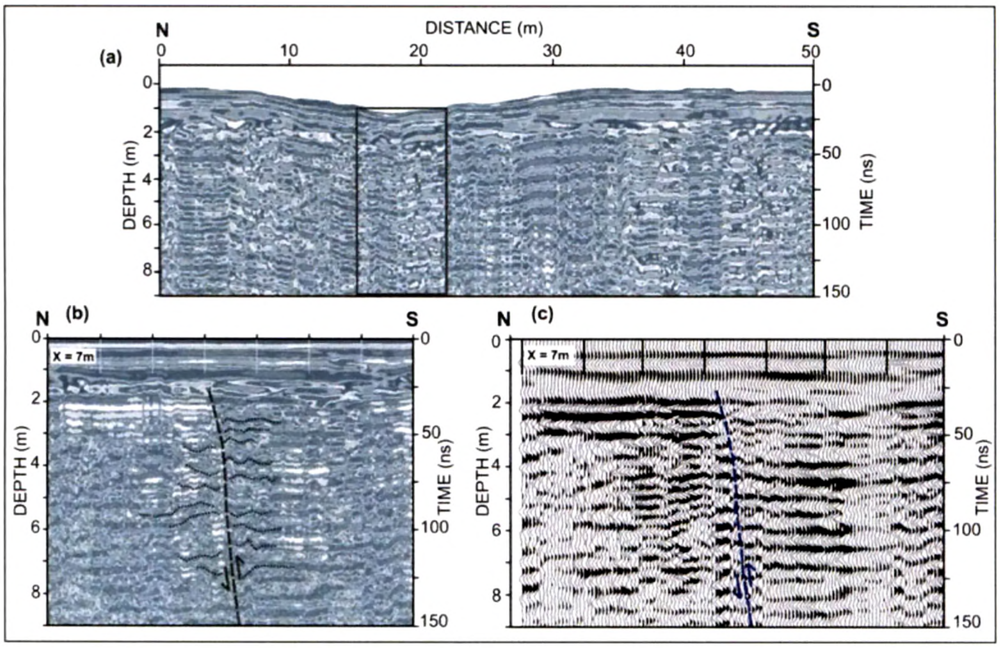

Figure 6.3 (a) 200 Mhz processed GPR profile obtained near Deshalpar. Enclosed area shows the location of the enlarged view shown in b and c. (b) Close up of the profile showing the fault plane of the KHF as picked up by GPR. (c) Same profile in wiggle format. Note the truncation of the reflectors along the fault plane.

along a 100 m long transect. The profile shows a zone of high amplitude reflections between 14-21 m that also exhibits signal scattering and truncation of reflectors. This kind of radar pattern is typical of faults that marks contrasts in lithology. The scattering of radar waves occur due to a thin zone of unconsolidated deposits like colluvium, clasts or breccia along the fault plane (Cai et al., 1996; Audru et al., 2001). The enlarged view of the KHF is shown in b. The profile also shows variable radar pattern on either side of the fault plane which is due to differing lithology. The reflections on the northern side of the fault mark the sandstones of Bhuj Formation while those to the south of it represent thin bedded shales and limestones of pre-Bhuj rocks. As seen in the interpreted GPR profile (Figure 6.3a, b and c) the KHF in the western part of the study area is a high angle south dipping reverse fault near the surface that becomes vertical at depth.

Site 2:GPR survey to the south of Bharasar

This survey site was situated to the South of Bharasar near Wandhay Talav (Figure 6.1). The area exhibits abrupt changes in the topography. The lithologies to the south are showing steep north facing scarp with gentle dip towards south. To the north of the scarp a manmade reservoir is present, which is named as Wandhay Talav. The northern part of the reservoir showing backing effect in the sandstone of Bhuj Formation. The geological setup of the area suggests lithotectonic contact of Bhuj and pre-Bhuj Formation within the dry bed of the reservoir area.

Satellite images and DEM interpretations are made to select the intersection of geological Formations prior to GPR profiling and then final survey was carried out to make out the possible fault zone. To the south of the KHF a linear ridge of 5-6 m elevation is running parallel to fault strike and close observation suggest folding and faulting in the shale rich lithology within the vicinity of fault zone. The GPR profile shown in Figure 6.4 is 20 m long in NW-SE direction is a part of 50 m long profile indicating contrast in reflection patterns. Discontinuous nature of ground waves indicates variation in soil moisture in upper surface sediments. A sharp reflection is picked throughout the profile near 35 ns, separating the scattered reflection in the bottom overlain by low energy returns in the upper part. A zone of highly scattered signals is picked near 14 m distance showing discontinuities and offsetting of the reflections along a plane. The interpretation of GPR profile suggesting a steep south dipping fault plane near 14 m distance (Figure 6.4a, b). The amplitude spectrum analyses suggest distinct energy reflections of varying strength variations from either side of the fault zone, also indicative of lithological variation.

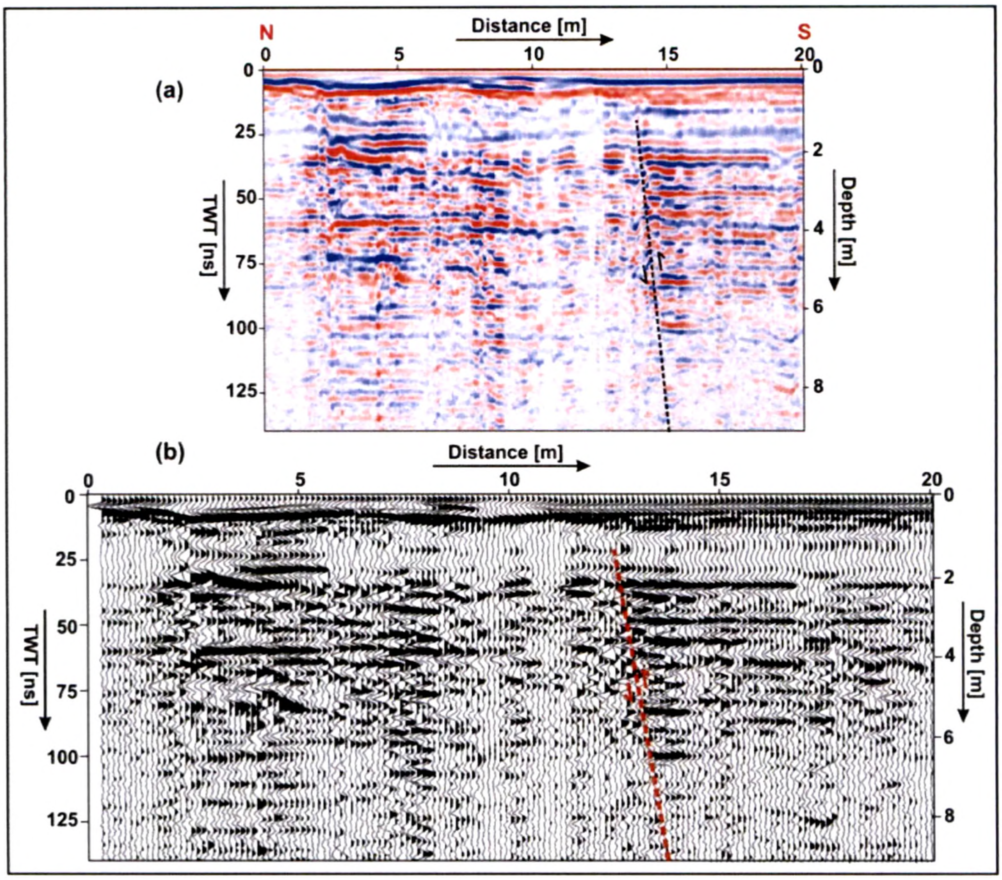

Figure 6.4 (a) GPR profile raised across the Katrol Hill Fault (KHF) near Wandhay talav. (b) GPR profile in wiggle mode showing truncation of the reflections near the fault plane. Variation in amplitude strength from either side of the fault is due to lithological contrast.

Site 3: GPR survey near Fakirwadi

This is one of the very important GPR survey site located near 5 km SW of Bhuj city at the Bhuj-Mandvi road (Figure 6.1). The radar data is showing good resolution and cluttered free signals at this site due to smooth surface and vegetation free environment. A 50 m long 2D GPR profile was obtained to accurately locate the position of the fault plane (Figure 6.5). The general direction of the profiling was north-south, which showing high amount of scattered signals from the upper part of the profile. The migration function was applied to reduce the consequence of diffractions. The reflections from the southern part of the profile have dominant of thinly layered discontinuous reflections which are abruptly terminating on fault plane near 34 m distance, where as the reflections from the northern part of the profile illustrating thick moderate amplitude returns, throughout the depth. The enlarged view

(28-40 m distance) of profile in wiggle mode is shown in Figure 6.5b, where fault plane is marked near 34 m distance. The discontinuous reflection pattern and strong hyperbolic reflections are picked from south of the fault which suggest upward dragging of the strata and interpreted as deformation signatures of subsurface lithologies. Interestingly, at this site a 10 m wide zone of scattered reflections with strong energy returns is marked in northern part of the profile indicating deformation in sandstone formations (Figure 6.5a, b).

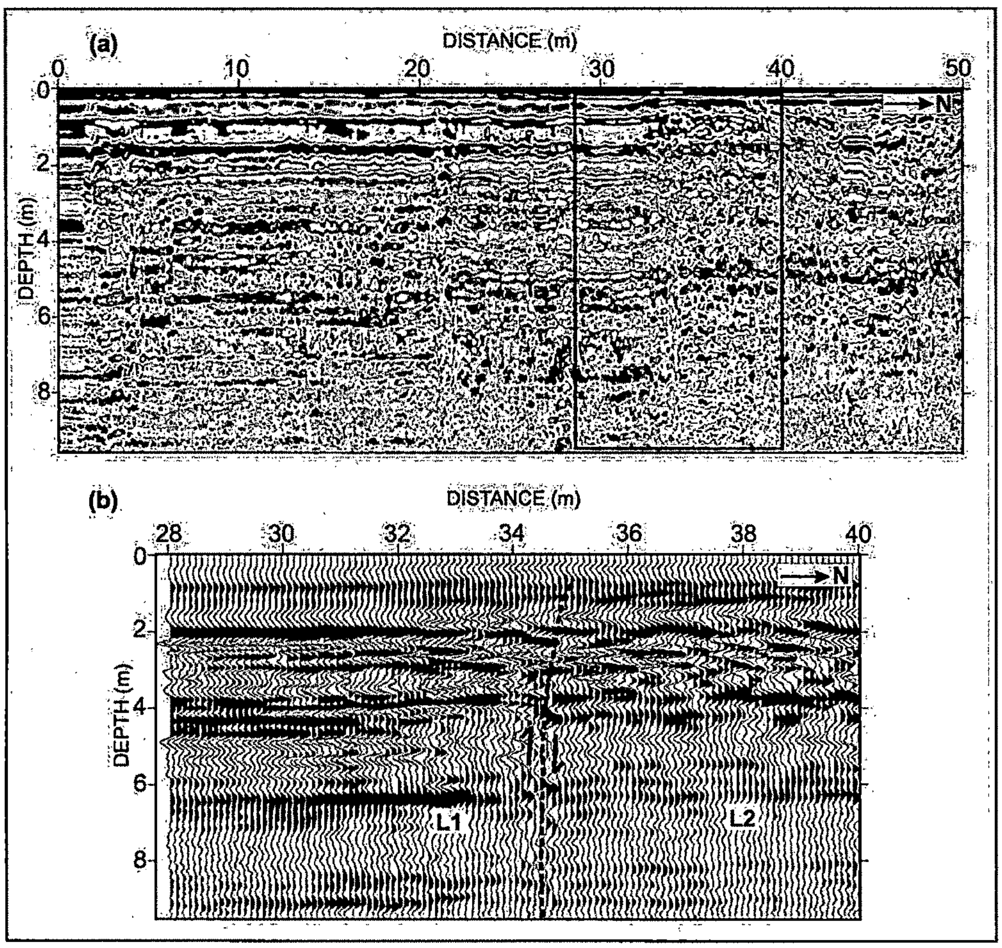

Figure 6.5 (a) 50 m long 200Mhz GPR profile collected from Fakirwadi near Shivparas Temple. (b) 12 m long migrated GPR data in wiggle format showing the fault zone. Fault plane is marked on the basis of termination of reflections. Lithological difference is observed by the variation in reflection pattern. L1- Low to moderate amplitude thin reflections, L2- Moderate amplitude thick reflections.

The 3D GPR survey was also carried out at the same site indicating deformation in the lithologies to the north (Maurya et al., 2005 and Patidar et al., 2006). To evaluate subsurface nature of KHF a 3D grid of 10x10 m is selected exactly above the fault strike. A separation distance of 1m was maintained between the transect lines along

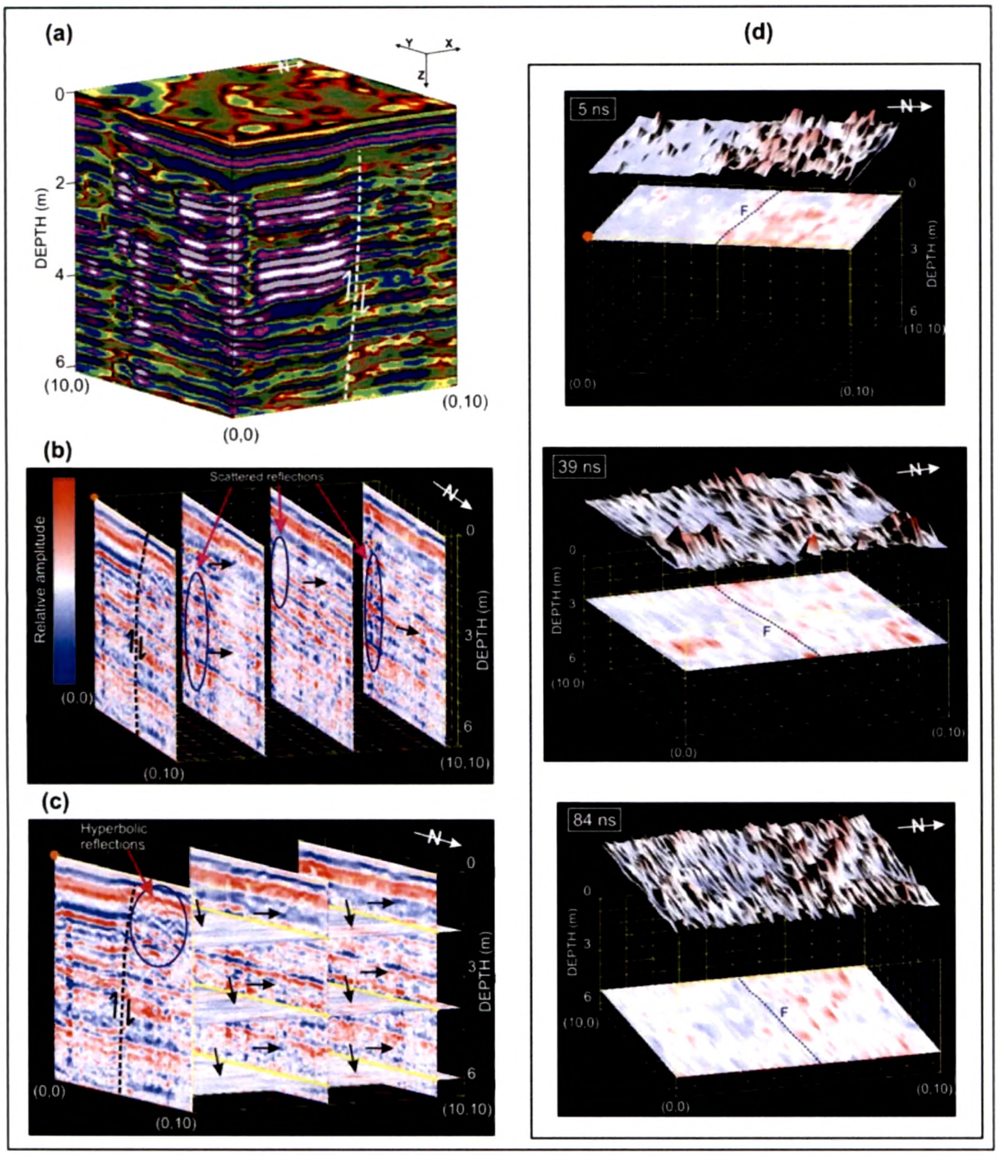

Figure 6.6 3D GPR data analysis. (a) Perspective view of 3D block showing Katrol Hill Fault. (b) Internal image of 3D GPR data. Diffraction of signals are marked over X-slices. (c) X and Z slices show the different positions of KHF and different reflection patterns from either side of the fault. The black arrows delineate the lateral extension of fault over Z-slices. (d) The amplitude contour plot generated using Horizontal slices (Time slices), illustrated from 3D GPR data at 5, 39 and 84 ns. The black line in the central part of the slices shows the position of KHF at different depth. The distinct changes in reflection pattern and amplitude strength are used to make out the position of the fault. The colour intensity is a function of amplitude.

both, X and Y directions (Figure 6.6). The migration function was applied to remove the high amount of diffractions coming from upper part of the profile. In the southern part of the profile thin reflections are dominating which abruptly change in to thick moderate amplitude reflections across the fault plane. The discontinuous reflection pattern and strong hyperbolic reflections to the south of fault indicate deformation due to movement along fault. Interestingly, a wide zone of sand rich lithology towards north of the fault show high amount of scattering with strong reflections. The fault plane is marked by the termination of the reflections and the signal offsetting. The geometry of the fault is clearly picked in 3D block whereas in multi-slicing mode, the lateral continuity of the fault plane and deformational features are analyzed (Figure 6.6a). Four X directional slices are shown in Figure 6.6b showing hyperbolic reflections and scattered signals near the fault plane. A meshing of X and Z slices are given in Figure 6.6c, which shows the geometry of fault plane in depth and their lateral continuity in X direction. The black arrows demarcate the possible positions of KHF. The observations of 3D data in movie mode suggest extreme deformation of lithologies from both the side of fault plane.

The time slice mapping and amplitude-contour analysis from various depth points suggest strong variation in reflection strength of the signals that can be due to lithological variation across the fault plane (Figure 6.6d). The amplitude contour mapping and time slice interpretation suggest that the KHF abruptly changes its vertical nature into high angle reverse fault when its appear to the surface. To make out the continuity of the fault plane and stratigraphic interpretations, a 30 m long GPR profile is raised using 40 Mhz bistatic antenna in Common offset mode. In the common offset mode transmitter and receiver antennas are placed at 2 m offset distance and their positions are increased by 20 cm step size (Figure 6.7a). The profile indicates extension of the KHF till 550 ns (~32 m depth) time window (Figure 6.7b).

Site 4: GPR survey near Tapkeshwari

This GPR survey site is located to the south of Bhuj on Bhuj-Tapkeshwari road (Figure 6.1). The profile is 45 m long raised along NE-SW oriented transect (Figure 6.8a). The upper part of the profile (~5 m) exhibits prominent reflections with high to moderate amplitude signals. However, the strength of the radar signals decreases with the depth due to attenuation. The enlarged view of the interpreted fault

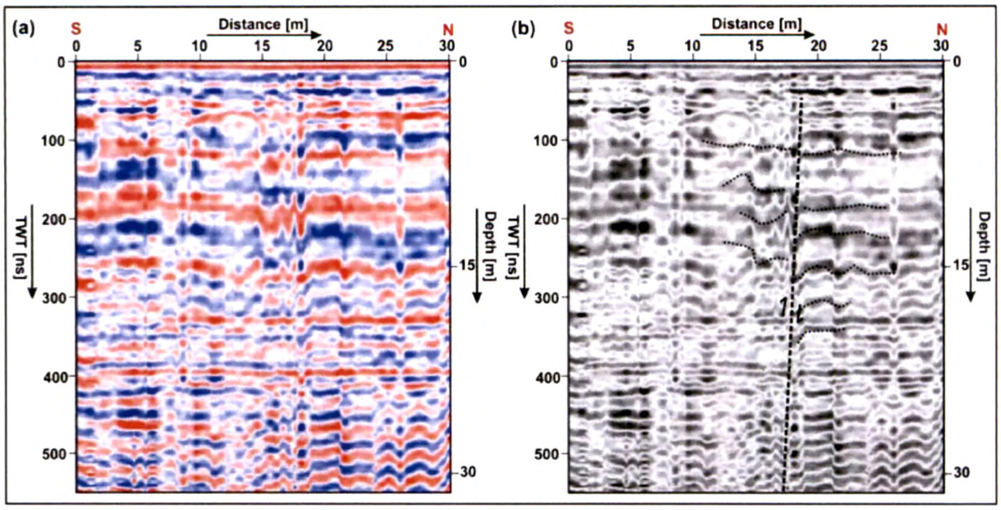

Figure 6.7 GPR profile taken by Common Offset method using 40 Mhz bistatic GPR antenna.

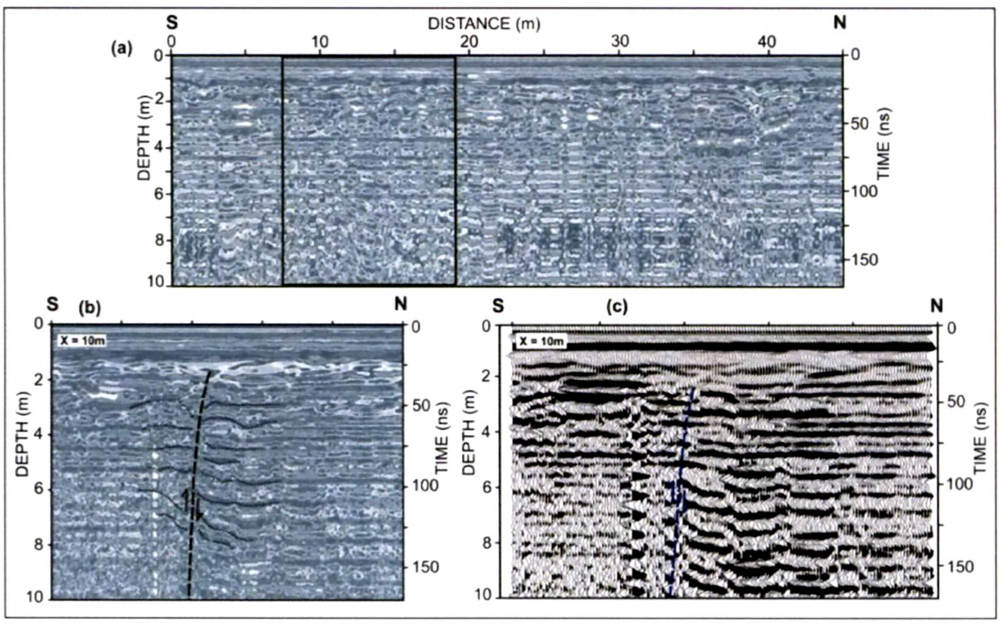

Figure 6.8 (a) GPR profile obtained using 200 Mhz antenna near Tapkeshwari. (b) Enlarged view of the part of the profile shown in a, with KHF. (c) Same part of the profile in wiggle format showing the fault plane.

zone shows all the primary characters needed to prove the presence of tectonic elements in GPR profiles (Figure 6.8b, c). Abrupt change in signal scattering, reflection patterns and amplitude strength is observed across the fault plane corresponding to lithological variations (Figure 6.8c). The SW part of the profile showing moderate amplitude signals at the upper half, which continuously attenuated with the depth. A high frequency vertical noise is overlapping to original signals near 2.5m distance, which may be due to poor ground coupling of antenna. To the NE of the fault, the profile shows repetitive truncation of reflectors along a line which is marked as a fault plane. The truncation of the reflectors is observed throughout the depth and suggests reverse nature of KHF.

Site 5:GPR survey near Mahadev Mandir

The profile was collected to the south of Madhapar village near Mahadev Mandir road (Figure 6.1). This site exhibits a thin layer of alluvium extensively used for agriculture purpose which has resulted in the masking of any surface expression of the faulting. The profile shown in Figure 6.9a is 100 m long and is raised by 200 Mhz frequency monostatic antenna. The thick reflection below the ground waves covers the entire length of the profile and is interpreted as the layer of reworked material (L1). A zone of scattered reflection appears at the centre. The horizontal reflections from the south are seen to change their dips and truncate near 45 m. The enlarged part of this zone is shown in Figure 6.9b.

The truncation of the reflections and the drastic contrast in reflection patterns across the fault plane/zone is clearly seen in wiggle format (Figure 6.9b). The reflections in the southern part of the profile comprise thin, low to moderate amplitude reflections and are separated by high amplitude returns further north. This repetitive nature of low and high amplitude returns is due to alternation of thinly bedded shale and sandstone of the pre-Bhuj Formation. The nature of the signals abruptly changes to high amplitude reflections across the fault plane which corresponds to medium to coarse grained sandstones of the Bhuj Formation. The reflection pattern of the radar signals indicate a wide zone of deformation in southern part of the fault plane which gradually decreases towards north. At this site the GPR data suggest that the limestones and shales of the pre-Bhuj Formation to the south of the fault show extreme deformation as tight folds and upward dragging of the strata due to movement along the KHF where as the sandstones of the Bhuj Formation to the north of the fault plane show little or no deformation. The frequency-amplitude spectrums from either sides of the fault plane suggest strong variation in the strength of reflected signals which correlates with contrasting electromagnetic conductivity of the sediments. The GPR data shows that KHF is a south dipping reverse fault.

Interestingly at this place, the fault plane was located just ~50 m north of the fault scarp. Therefore at this place the scarp retreat is much less then other sites located towards east.

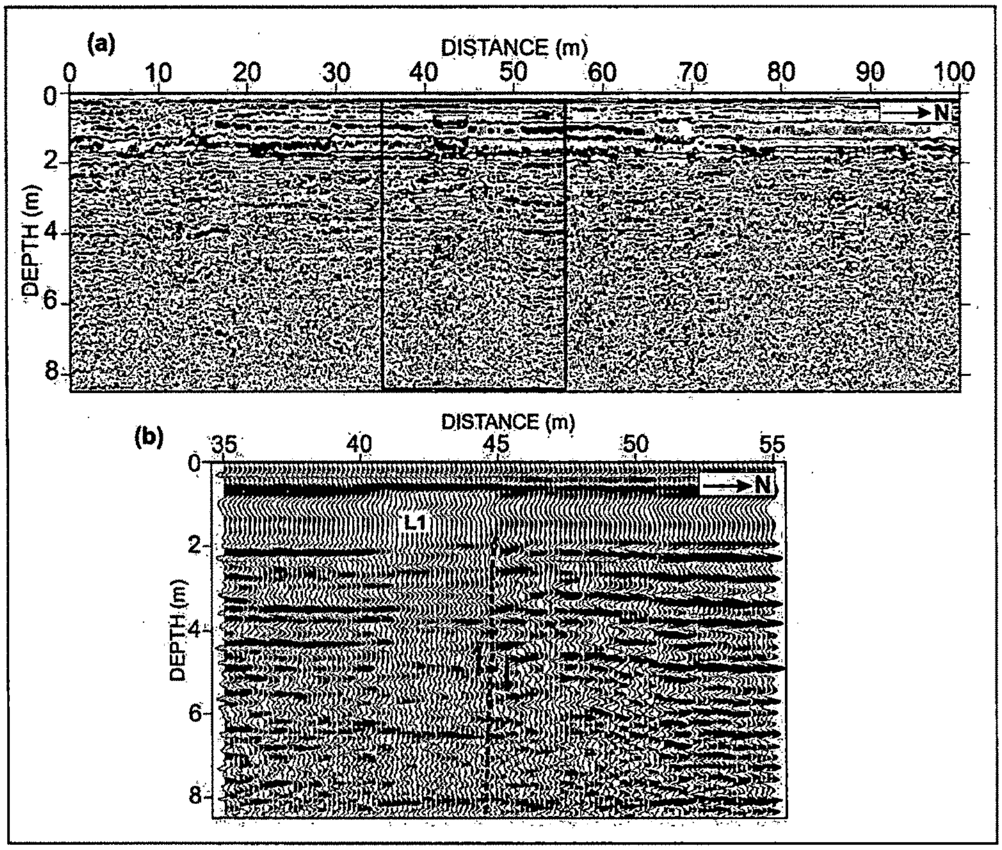

Figure 6.9 (a) 100 m long GPR profile taken near Mahadev Mandir using 200 Mhz antenna. Enlarged area shows the part of profile reproduced in b. (b) 20 m long wiggle profile of selected part shown in a. L1- Layer of homogenous reflection generated by thin alluvium cover. Note the contrast in reflection pattern from either side of the fault plane. Termination of reflection patterns through out the depth near 10 m indicates the location of KHF.

Site 6: GPR survey near Khatrod

This site was narrowed down after extensive field mapping, satellite image interpretation and DEM modeling which indicate some low altitude elongated ridges parallel to fault strike at the hanging wall. The north facing steep Khatrod scarp is located towards south of this features (Figure 6.1). This site shows impressive geomorphic expression of scarp similar to the sites located to the south of Bharasar. A N-S oriented 100 m long GPR transect is selected perpendicular to the direction of linear ridges to appreciate their role in recent tectonic activities. Four meter topographic corrections along the GPR transect line which was corrected in post survey data processing using Surface normalization function (Figure 6.10). Two high amplitude continuous reflections from top of the profile are marked as direct air and ground waves. The upper part of the profile show moderate to high amplitude returns with scattering of signals at various spots (Figure 6.10). The southern part of the profile is characterized by continuous reflections from upper level and low energy returns from deeper level whereas the northern part shows uniformly high energy returns throughout the profile. The scattering of radar waves seen in the upper half of the profile from 5-14 m distance is due to a dry channel filled with coarse grained transported material.

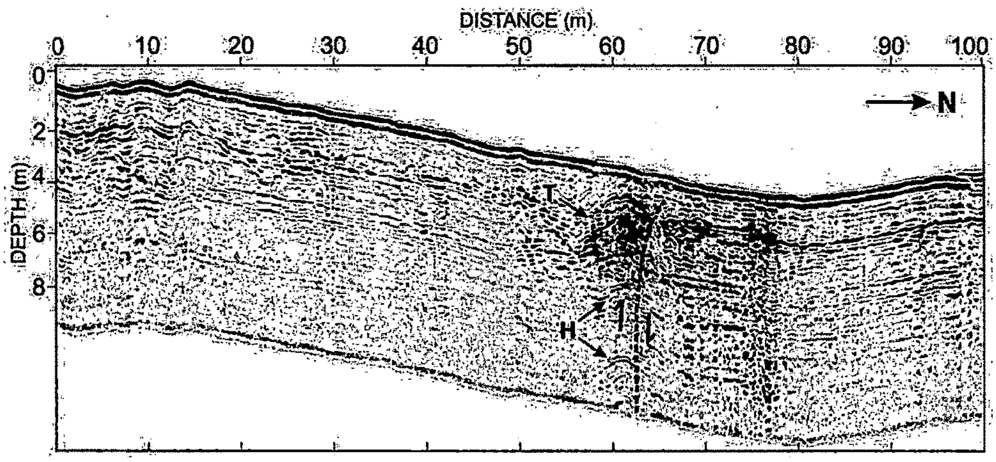

Figure 6.10 200 Mhz GPR profile collected across the Katrol Hill Fault near Khatrod. Surface normalization and time/depth conversion is applied to the data. Black line indicates possible position of the KHF. T- Terminated reflections, H- Hyperbolic reflections.

A second zone of highly scattered radar signals is observed between 57-65 m (Figure 6.10). The change in reflection pattern across this zone is suggestive of the fault zone. The complex reflection patterns, strong hyperbolic reflections and reflection truncation support the interpretation. According to Gross et al (2004) the diffraction hyperbolas probably originate from the termination of structures against the fault plane. The strong contrast in reflection patterns across the fault plane is attributed to lithological contrast on either side of the fault. The wide zone of discontinuous reflections from the south of fault plane suggest high amount of deformation in shale rich lithologies due to movement along the KHF whereas the sand rich lithologies to the north exhibit a narrow zone of deFormation close to the fault. The GPR profile at this site shows that the KHF is a south dipping near vertical reverse fault. The GPR profile revealed that the KHF is located about 800 m towards north from the base of the Khatrod scarp. This is attributed to the retreat of the fault scarp and demonstrates the utility of the GPR in precisely locating the fault and determining fault scarp retreat.

Site 7: GPR survey near Wavdi

This profile was obtained near Wavdi village located at the eastern extremity of the study area (Figures 6.1, 6.11a). The GPR profile is 20 m long and is oriented in

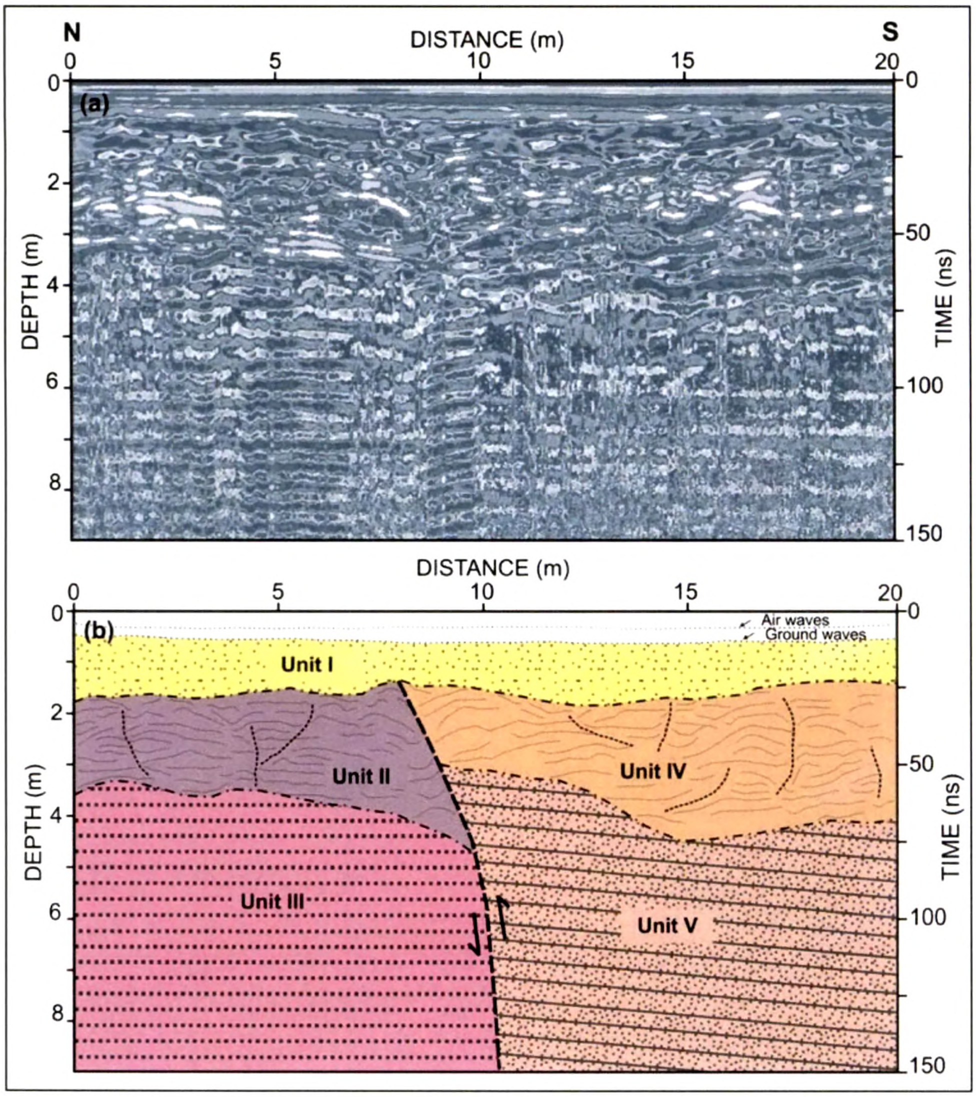

Figure 6.11 (a) 200 Mhz GPR profile across the KHF near Wavdi. (b) Interpreted section showing units I-V marked on the basis of distinct radar signatures.

N-S direction (Figure 6.11a). The entire profile shows four distinct sets of radar signals(Figure 6.11a, b). The frequency spectrum, amplitude strength and radar wave patterns suggest five distinct lithological units (I-V). Unit-I is the thin surfacial soil cover. Unit-II is the crushed and sheared sandstone, which overlies the massive sandstone below (Unit-III). To the south of the fault plane, Unit-IV also represents the sheared fine grained rocks, below which massive rocks (Unit-V) are present. The thinner and wavy reflectors of the Units-IV and V suggest finer grained lithology, possibly shales. In general, the Units-I and III corresponding to sheared rocks show high amplitude continuous reflections from the north, show abrupt change in the dips and truncate over the fault plane. These diffused signals are the result of attenuation of the signals by weathered material. The profile shows that the KHF changes its nature from steeply dipping reverse fault in the near surface to vertical fault at deeper levels.

GPR investigations along the KHF indicate that it is a south-dipping high-angle reverse fault near the surface and vertical at depth. The fault is easily mapped by the sharp lithological contrast reflected in the profiles. The limestones and shales of the pre-Bhuj Formation to the south of the fault, in general, show higher intensity of deformation in comparison to sandstones of the Bhuj Formation to the north of the fault which show much less degree of deFormation.

Site 8:GPR survey along Transverse faults

The transverse faults of the southern part of the Kachchh have a significant role in tectonic evolution of the southern Mainland Kachchh. These faults are showing imprints of recent tectonic activities over the present day landscape. GPR survey was carried out along two transverse faults to understand their subsurface behaviour. These faults are situated in the western part of the Katrol Hill Range. The first site is present to the south of Bharasar village (Figure 6.12). This is one of the major fault of Katrol Hill Range, which is displacing to KHF at hundreds of meter and running NW-SE. The transect lines are selected perpendicular to the fault orientation and 200 Mhz antenna frequency is used to collect the data. The profiles showing enormous effects of faulting on either side of the fault (Figure 6.12). The vertical nature of the main fault at the depth and some other minor faults are interpreted on the basis of reflection truncation and offsetting.

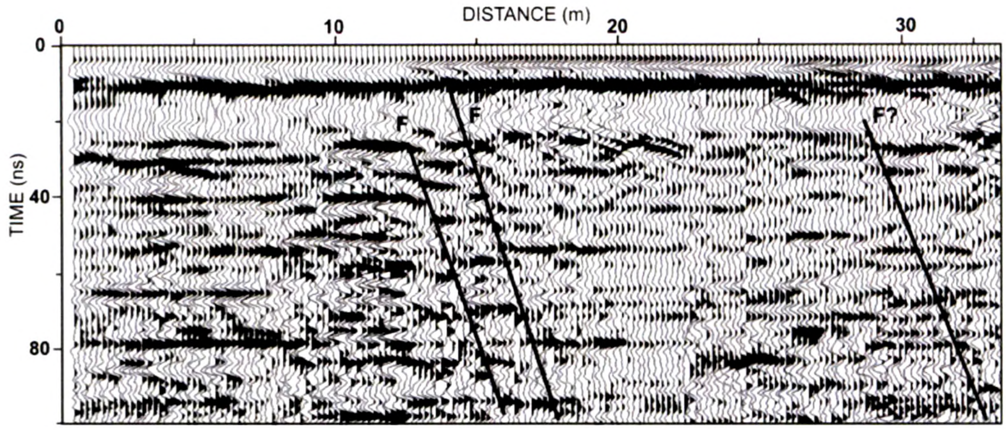

Figure 6.12 GPR profile carried out across a transverse fault to the south of Bharasar village showing highly scattered signals representing to extensive deformation with in the vicinity of the fault plane/zone.

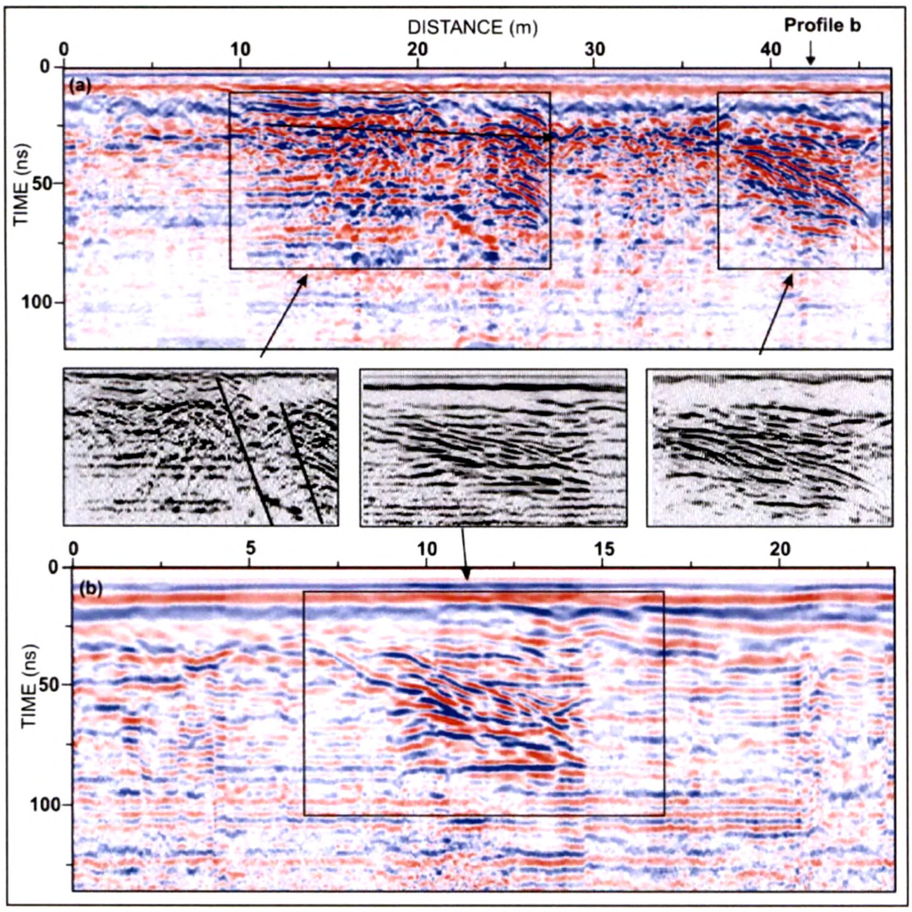

Figure 6.13 GPR profiles across a transverse fault. (a) 200 Mhz GPR profile collected from the west of Mankuva showing truncated reflections near the fault plane. (b) GPR profile perpendicular to the profile shown in a, showing deformation in subsurface.

The second transverse fault is present to the east of the Mankuva (Figure 6.1). This transverse fault does not displace to the KHF, but it is showing vital indications of the recent faulting. The well preserved slickensides and incision in sandstone on the upthrown block suggest rapid upliftment of the area. The GPR profile is raised to understand the deformational pattern and subsurface nature of the fault. The radar data suggest some vital information about the near surface structures and orientation of the fault. GPR profile indicating that the strata at the shallow depth are dipping towards SW and the other perpendicular profile showing dip towards the south (Figure 6.13). The fence diagram of the near surface lithology and structures based on GPR are suggesting domal shaped structure truncating over the fault, which do not have any signatures over the surface. These structures are continuing up to the 10 m depth.

THE KHF AS REVEALED BY GPR IMAGING

The KHF is an E-W trending intrabasinal fault that marks the lithotectonic contact between rocks older than Bhuj Formation to the south and the Bhuj Formation of Late Cretaceous age to the north (Biswas and Deshpande, 1970). The fault significantly influences the tectonic set up of southern Mainland Kachchh as it marks the northern margin of the tilt block. The north facing fault scarp displays a prominent geomorphic expression, which marks the boundary between the rugged mountainous terrain of the Katrol Hill Range to the south and the low lying rocky plain to the north. Due to offsetting along the transverse faults, the KHF present complex tectonic setting. In the absence of subsurface mapping, the KHF is generally marked at the base of range front scarp. However, the present study suggests that the actual fault plane is located further north of the scarp line.

The GPR proved its efficiency to locate the active fault strand of KHF without disturbing the local conditions. In the GPR profiles the main fault strand of the KHF shows variable near surface characteristics ranging from steeply dipping reverse fault to vertical. The changes in the nature of the fault plane may be attributed to the role of transverse faults in controlling the tectonic behaviour and stress release along the KHF. The GPR profiles along the KHF indicate remarkable changes in attitude (Figure 6.1) and subsurface nature along the length from Wavdi (east) to Desalpar (west). The variable amount of scarp retreat suggests that various fault segments may have been active at different times and may also be reflecting varying intensities of tectonic activity along the length of the fault. The 3D GPR data reveals important information about the subsurface geometry and associated deformation along the KHF. The lithology to the south of the fault plane shows extensive deformation compared to northern part. The present study demonstrates that the of GPR studies when combined with the field mapping, satellite data interpretation and digital elevation modeling is particularly revealing in the active fault investigations.