CHAPTER-8

GROUND PENETRATING RADAR (GPR) STUDIES

IMPORTANCE OF GPR TECHNIQUE IN ACTIVE FAULT STUDIES

In geology, use of Ground Penetrating Radar (GPR) technique has been proved to be a powerful tool in fault studies around the globe. Accurate mapping of active fault zones is important to understand the behavior of active fault planes in the recent past (Green et al. 2003; Salvi et al. 2003). Use of GPR to detect and analyze the nature and architecture of active fault zones and faults in shallow subsurface is well known (e.g. Christie et al., 2009, Dora et al., 2006; Demanet et al. 2001; Rashed et al., 2003). High-resolution GPR surveying provides a means to image shallow complex structures not evident at the surface (e.g. Smith and Jol, 1995; Yetton and Nobes, 1998; Green et al., 2003; Liberty et al., 2003; Gross et al., 2004; Tronicke et al., 2006; McClymont et al., 2008a, 2008b). Several GPR applications to palaeoseismological studies for imaging active fault are found in the literature (i.e. Grasmueck, 1996; Gross et al., 2000; Demanet et al., 2001; Bristow and Jol, 2003; Rashed et al., 2003; Reiss et al., 2003; Maurya et al., 2005, Pauselli et al. 2010) providing high-resolution images of the subsurface without damaging the surrounding environment.

It has been proved that the faulted geological horizons are good radar reflectors. Displacement along the fault plane could affect the host material in several ways which depends on the type of material and the type of movement along the fault. In such areas, reflections from the faults themselves are less common, but diffractions associated with horizons truncated by faults are common (Gross, 2004; McClymont, 2008; Venneste et al., 2008). Also 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). GPR survey over the faulted terrain generates such type of reflection pattern that can be interpreted on the basis of certain criteria. It has been proved that there the faulting actives are reflected by certain pattern of the GPR reflection. Basson et al. (2002) have established three main criteria (and their combination) for the interpretation of various types of the fault movements: minor discontinuities of reflectors (minor offsets or thickness variations), which indicate fractures; 2) abrupt unconformities and sudden variation of lateral reflectors, which is indicative of a strike slip component; 3) vertical displacements of reflectors, which indicate either normal or reverse faults with dominant dip-slip motion and with sub-horizontal bedding.

RECOGNITION OF NSF IN GPR DATA

Recognition of NSF in the GPR profiles is based on the certain characteristics of the reflections. However, the appearance of the reflections in the processed GPR profiles of the four segments is different. This is attributed to the change in the field setting of the NSF in terms of rock type and rock property over which GPR surveys conducted. As discussed in the previous chapters, the probable location of the NSF rock types varies in all four segments. Accordingly, in segment I, II and III, NSF is located within the Deccan Trap. Whereas, in segment IV, NSF is demarcated over the deformed Tertiary rocks and in the extreme western part, it is within the Quaternary sediments. This has resulted into the variation in the amplitude and pattern of GPR reflections. Thus, to recognize NSF in the processed GPR profiles proper criteria applied for different profiles and also correlated with the field setting.

Recognition of NSF in GPR profiles is based mainly on two characteristics of the reflectors which correlatble with the field setting. These include vertical displacement of the reflections and sudden change in the pattern of the reflection. GPR surveys in segment I, II and III were carried out over the Deccan traps. While in segment IV, one profile conducted over the Tertiary sedimentary rocks and another one on loose Pleistocene sediments. Hence, the GPR surveys conducted over the terrain comprise of one rock type at particular site. However, the tectonic movements along the NSF have altered the original rock properties. The faulting activities have indirectly changed the properties of the rocks by shearing and crushing caused during the fault movements. The crushing of the rocks have accelerated the weathering process and developed good amount of clay material. This has made easy to identify fault zone and to locate the master fault within that zone. In the GPR profiles, sheared rocks that enriched in clayey part show low amplitude reflection pattern, and the displacement within such zone made possible to locate the master fault NSF. However, a single recognition character is not applicable to all of the profiles; instead, each site has its own recognition criteria. Hence, in the processed GPR profile, faulting activity that relate to the NSF is represented by displacement of the reflection, occurrence of hyperbola or combination of both of the criteria.

SELECTION OF SITES FOR GPR STUDIES

GPR survey sites were selected on the basis of detailed study of the geomorphic analysis and extensive field visit. On the basis of geomorphic analysis several important spots were identified along the length of the NSF in all four segments. And as discussed in the previous chapters, the geomorphology of the study area suggests that the probable

location of NSF is in the vicinity of the scarps. On this basis, all the sites werelocated in the vicinity of mountain scarp. Of this, accessible sites were visited for the verification, to understand the field setting of NSF and to decide the trend and location of the GPR survey-line. At some of the location morphotectonic setting and field exposures provided good evidences of the faulting activities which made easy to decided survey locations. For example, one of the sites which were selected for the field visit on the basis of anomalous geomorphic characters was studied in the initial stages of the present work. At this site, the stream that flows across the NSF has incised the basaltic terrain and made available good incised exposures where the fault zone could be identified. This made easy to locate the survey line and trace the NSF within that fault zone. However at few localities the field exposures were poor, in such condition, GPR survey line decided with the help of morphotectonic setting of that particular site. After studying the survey site thoroughly and identifying the fault zone, the GPR survey lines were decided along the fault zone. During the survey, initial profiles were acquired to decide the proper file header parameters for that particular survey site. This was followed by acquisition of GPR profiles along the survey-line.

In this chapter, nine profiles from all four segments (Fig. 8.1) that represent NSF precisely are presented and discussed segment-wise. These include three profiles in segment I, located near Gora Village, Umarwa and Chakva; three profiles in segment II, located near Sanedra, Jhuna Ghanta and Wali; one profile form segment III, located near Kapat and; two profiles from segment IV, located near Jhagadia and Karad.

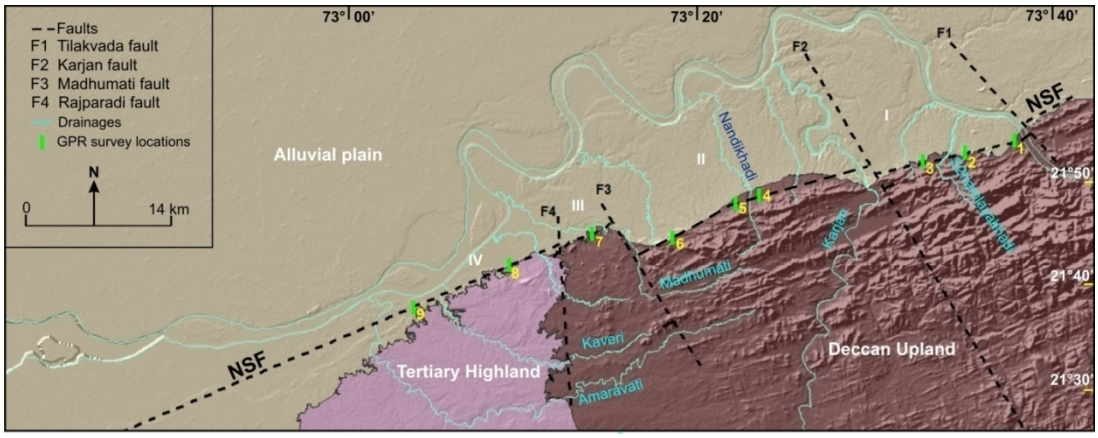

Figure 8.1 Map showing the locations of the GPR survey sites. I to IV are the morphotectonic segments of the study area.

Velocity analysis

To know the precise Dielectric Constant of the host material and for the depth correction, velocity analysis was carried out at several locations using the bistatic Multiple

Low Frequency (MLF) antenna. The velocity profiles were generated during the GPR survey using Common Midpoint (CMP) method. This method generally used to analyze the variable velocity and density layers of the shallow subsurface (Huisman et al., 2003; Jol and Bristow 2003). The CMP profiles are obtained using 80 Mhz bistatic GPR antenna in a point mode, where the orientation of the antennas is perpendicular to the electric field polarization. The measurements are taken by manually shifting to transmitter and receiver from a mid point to opposite directions up to a maximum distance. For this, the initial offset was fixed on 1.25 m, while the transmitter and receiver were shifted in opposite directions by 25 cm step size up to the maximum distance, with two-way travel time window of 200 ns. Ultimately, result of the survey provides a plot between antennas separation (offset distance between antennas) and two way travel time.

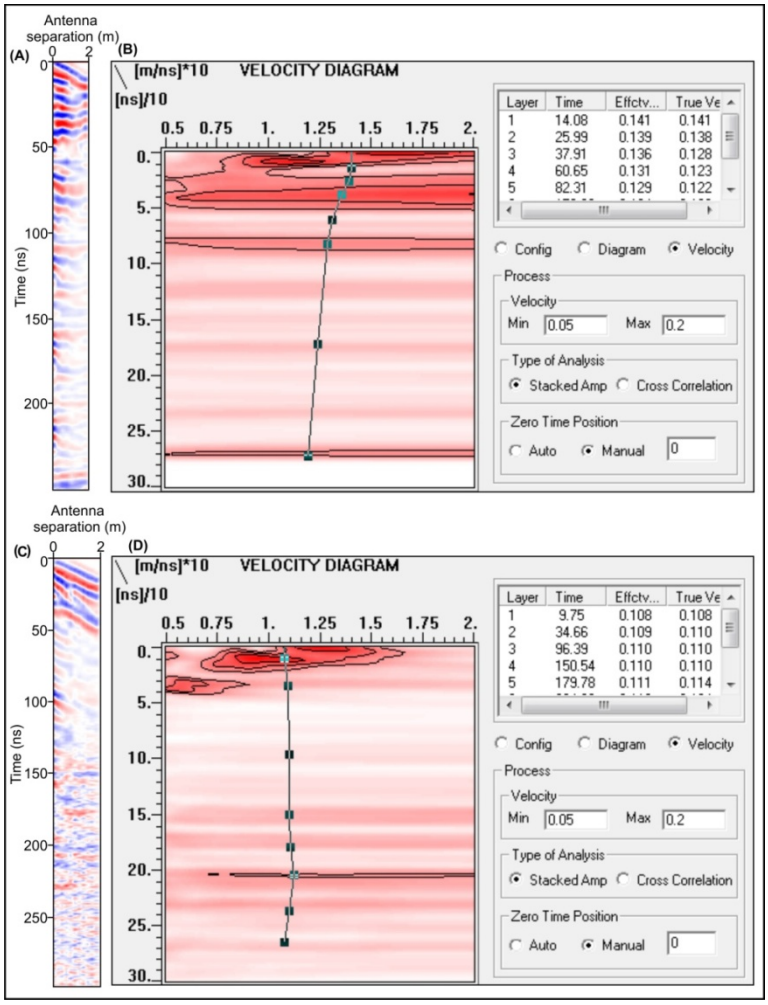

Figure 8.2 (A) Processed CMP profile taken over the basaltic flows at Gora colony. (B) Velocity diagram of the CMP profile shown in A. (C) Processed CMP profile taken over the Tertiary rocks near Jhagadia. (D) Velocity diagram of the CMP profile shown in B.

The survey conducted separately over the basaltic flows of Deccan Trap formation and Tertiary sedimentary rocks. Two representative CMP profiles are shown in Fig. 8.2. In

the post processing step these velocity profiles used to compute the velocity by plotting the multioffset data on a graph of velocity versus two-way zero-offset travel time. The obtained true average velocity values of Deccan Traps and Tertiary rocks are 0.11 m/ns and 0.12 m/ns respectively (Fig. 8.2). The average velocities were used for time/depth conversion because, when GPR survey carried out along vertically displaced strata, the average velocity which shows good spatial correlation in the depth correction is used (McClymont et al. 2010; Pauselli et al. 2010; Denith et.al. 2010).

GPR studies in the Segment I

In the segment I, GPR surveys were carried out at Gora colony, Umarwa and Chakva using 200 MHz and 80 MHz antenna. Several profiles acquired across the trend of NSF. However, at places profiles acquired using 80 MHz antenna gave satisfactory results in terms of resolution and depth, while at few locations 200MHz provided good repetitive profiles. Accordingly, the profiles that gave satisfactory results at particular location are interpreted and discussed below in this chapter.

Site 1 is located in the village named Gora colony which near the left bank of Narmada River. Here, the Mesozoic rocks of Bagh formation are outcropped as inliers. The Mesozoic rocks comprises of intercalated sequence of sandstone, shale and few outcrops of limestone. The rocks are highly deformed and fractured. This is related to the phase of tectonic upliftment occurred in the late Cretaceous time during which the NSF reactivated as a reverse fault and made a tectonic contact between rocks of Bagh formation and traps. To the north of the scarpline basaltic rocks continue for a short distance and abuts against Quaternary sediments. The upliftment along the NSF has generated steep gradient in the alluvial plain to the north of scarpline. With this knowledge of geomorphological and structural background that firmly supports the probable location of NSF scarp, GPR survey was carried out across the scarp. The GPR surveys were carried out over a 26 m long survey-line the oriented in N-S direction line using 80 MHz and 200 MHz antenna through methodology of common offset mode and by continuous dragging respectively. The data was processed as described earlier in the Chapter 3. Surface normalization was required as the data was obtained over undulated ground. In the processed profile along the depth, there are three different types of radar facies (Fig. 8.3). There is a layer of parallel reflections of strong amplitude occur up to the depth of almost 1 m. This layer represents thin cover of alluvium seen over the surface. This is followed by a thick layer that ranges up to 9 m and comprises of reflections of low amplitude, wavy and dipping.

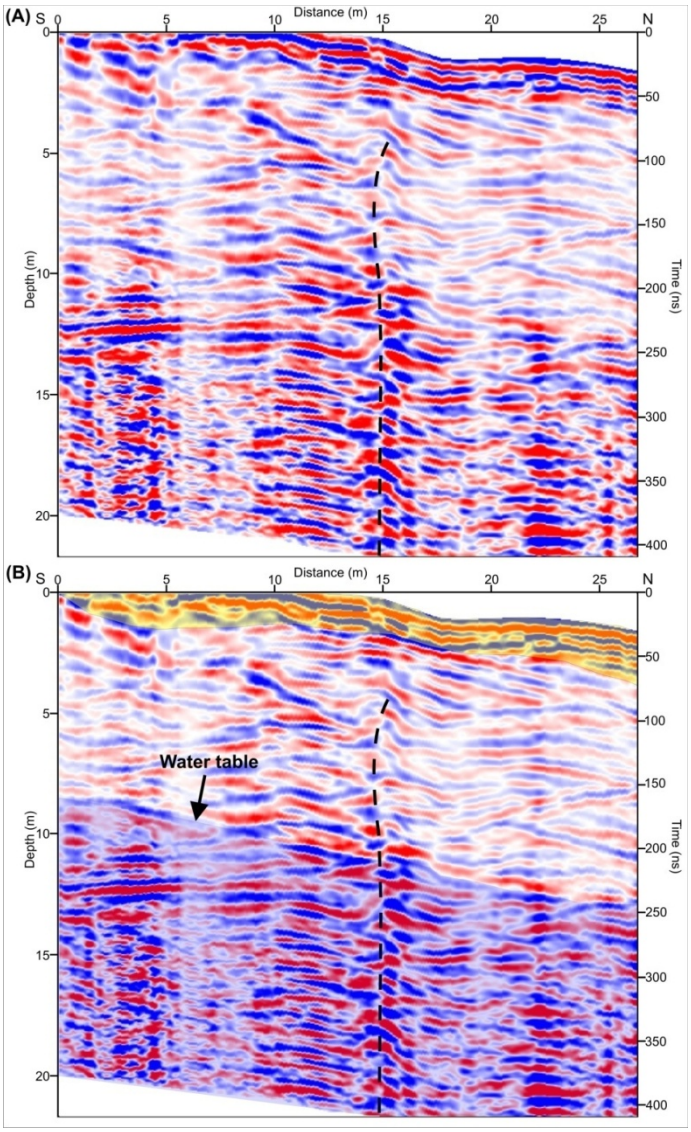

Figure 8.3 (A) GPR profile taken at Gora colony (site 1) using 80 MHz bistatic antenna. Note the displacement and hyperbolic reflections emanating from the fault plane at ~15m. (B)Interpreted section of the profile shown in A.

As discussed earlier, the rocks are deformed, highly fractured and weathered making the radar facies complex to discriminate and interpret. The close examination of the reflection pattern indicates that the reflections that are in the southern part of the profile are dipping in the south, while reflections in the northern part of the profile are dipping in the north direction. At ~9 m, there is a thin layer of high amplitude which is continuous and dipping in the south is a water table. Below 9 m, rocks are under water, highly weathered and fractured making radar reflections of poor quality. The conspicuous characteristic is observed at distance of 15 m (Fig. 8.3). Along the distance in the profile, there is a displacement seen in the reflections at 15 m that combined with the occurrence of hyperbolic diffraction. However, this is not manifested over the surface. According to the

profile, it is seen up to 3 m along the depth scale. The occurrence of displacement and hyperbola indicate faulting activity.

The occurrence of hyperbola could be because of the boulders or fault related structure. The hyperbola is produced due to diffraction of radar waves from the steep fault plane (Ferry et al., 2004; Pauselli et al., 2010). Further the change in the amplitude and dip of the reflection to the north and south of the fault that visible in the radar facies of middle layer indicate contact between Mesozoic rocks and basaltic flows of Deccan Trap formation. All these characters strongly indicate tectonic movement that relatesto NSF. Accordingly, the radar facies suggest that the fault is vertical in depth and becomes southward dipping reverse fault as it approaches the surface.

Site 2 is located near the Umarwa village. The GPR survey carried out at the left bank (looking at downstream) of small stream emerging in the trappean upland in south and flowing to the north i.e. across the NSF. In the field, a ridge of the basalt is exposed over the surface and incised by the stream. The rocks were highly fractures, sheared and incised by the river. In the river channel, incised section shows sheared basaltic rocks which extends northwards for few meters and abuts again the alluvium. The exposed ridge sections were studied along the channel and fault zone was identified. The strike of the fault zone was noted and verified with the fault zone location of the previous GPR survey site 1. The result shows that the both fault zones were located over the same strike. Accordingly, GPR survey line was decided and survey was carried out across the fault zone.

A 20 m long S-N profile was collected using 80 MHz and 200 MHz antenna through methodology of common offset mode and by continuous dragging respectively. The 80 MHz antenna provided satisfactory results which is included in this section. Surface normalization was not required as the data was obtained over flat surface. In the interpreted profile radar facies of the top 1-2 m belong to the thin alluvium cover (Fig. 8.4). Below which, the profile comprises of reflections from the basaltic rocks. There is a water table at depth of ~7 m. Hence, the radar reflections below 7 m are comparatively of poor quality. There is conspicuous change in the pattern reflections observed at 10 m along the distance (Fig. 8.4). In the southern part of the profile, along the distance of 0 m to almost10 m reflections are horizontal. At 10 m there is visible displacement and beyond which the horizontality of the reflections is replaced by southern dipping pattern (Fig. 8.4). This characteristic indicates faulting activity. It is inferred that the NSF is vertical and becomes southward dipping reverse fault as it approaches the surface.

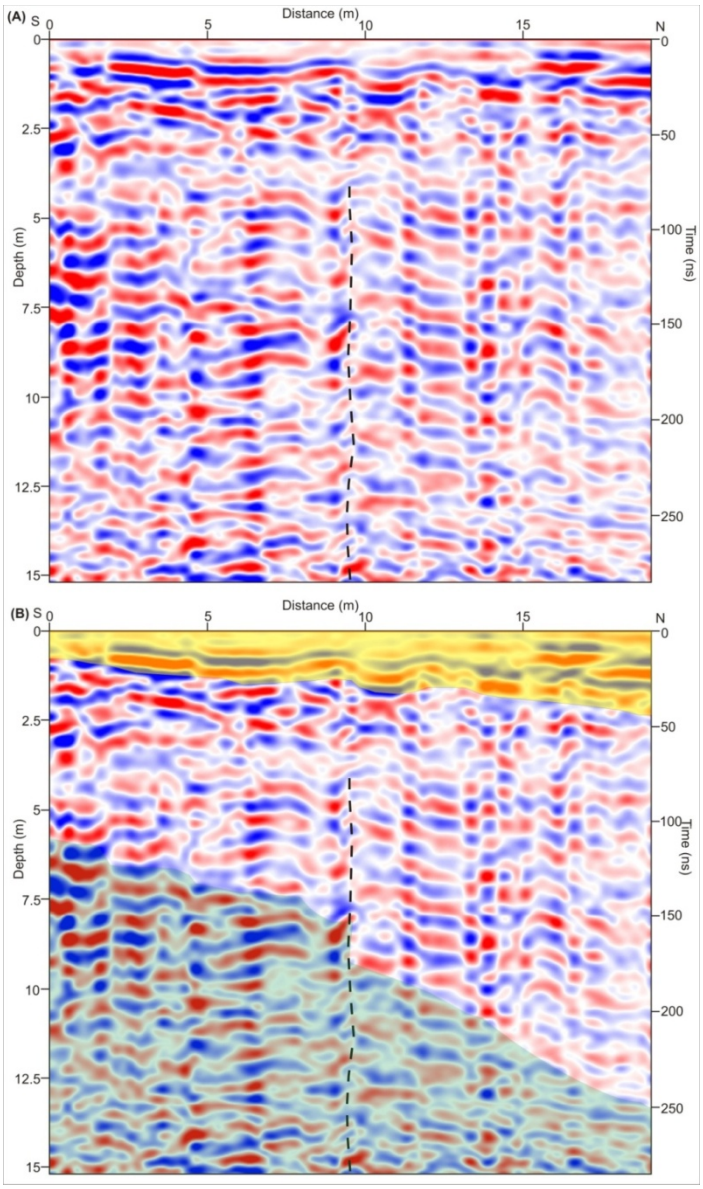

Figure 8.4 (A) GPR profile taken near Umarwa (site 2) using 80 MHz bistatic antenna. Note the vertical displacement indicating the fault plane at ~10m. (B) Interpreted section of the profile shown in A.

Site 3 is located near the Chakva village. The GPR survey site was selected on the basis of conspicuous morphotectonic setting. In the field, the ridge comprises of sheared, gouge like basaltic rocks occur in the trend of NSF i.e. ENE-WSW. The ridge demarcates the northern limit of the basaltic terrain and southern limit of alluvial plain. The GPR survey line was oriented across the trend of the ridge. The GPR profiles were generated over the flat surface using 80 MHz antenna in biastatic mode. In the processed profile, the upper most part along the depth of 0 to ~5 m comprises of the radar reflection from the alluvial cover (Fig. 8.5). At ~5 m there is a strong undulated reflection which continues all along the distance of the profile. This could be related to the reflection from the former topography of the terrain which is now covered by alluvium. Below 5 m the profile shows reflection from

the basalt. There is a water table identified at depth of ~19 m. The significant feature in the profile observed below 5 m depth and at distance of 6 m. There is a bifurcation of the reflections and break in the continuity (Fig. 8.5). The bifurcation of the reflection could be related to the diffraction of the radar waves due to the occurrence of steep wall like scarp. As there is a displacement along the scarp it can be interpreted as fault scarp. These characteristics suggest the probable location of the NSF in the subsurface. The close study of the pattern of the displacement seen in the reflection suggests that the NSF is vertical in the depth and becomes reverse as it approaches the surface.

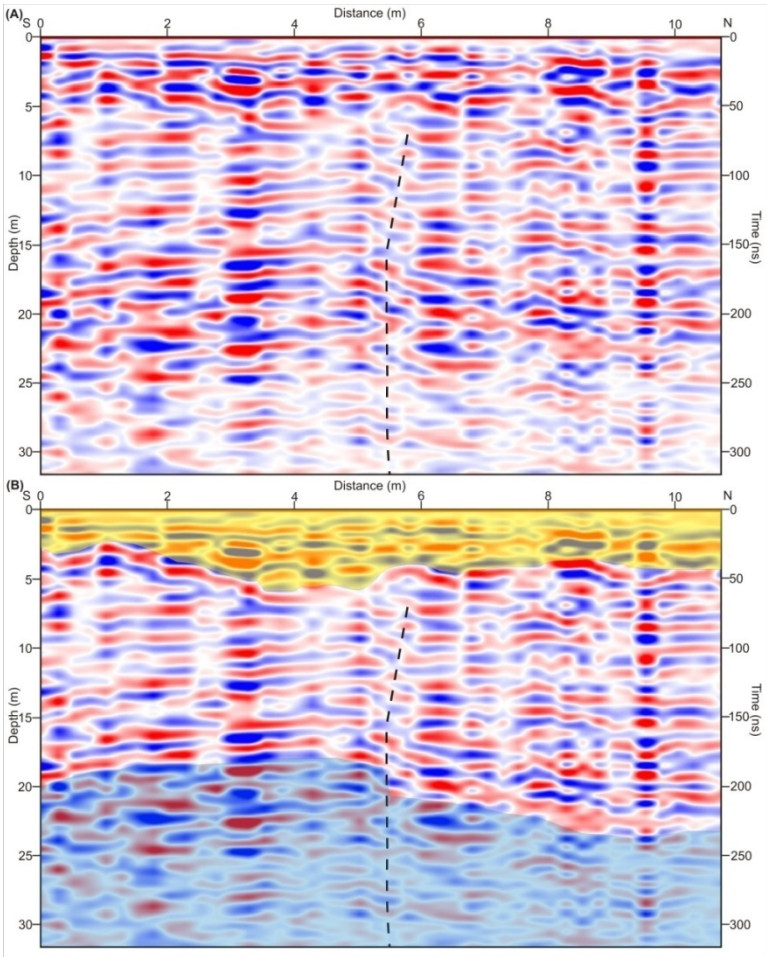

Figure 8.5 (A) GPR profile taken near Chakva (site 3) using 80 MHz bistatic antenna. Note the bifurcation of the reflections and vertical displacement that indicating the fault plane at distance of ~6m and below depth of 5m. (B) Interpreted section of the profile shown in A.

GPR studies in the Segment II

In segment II GPR surveys carried out at three locations near the villages named Sanedra, Jhuna Ghanta and Wali. As discussed in Chapter 4, segment II is tectonically most active segment of the study area which is also reflected in the field setting and rock property of the rocks of this segment. The rocks of this segment are comparatively highly sheared and fractured than that of the rocks of the other segment. Hence, GPR profiles of this

segment show comparatively low amplitude reflections then the profiles of the other segments. The GPR survey conducted using 80 MHz and 200 MHz antenna. The profiles of the GPR survey that conducted using 80 MHz antenna has provided satisfactory result for all three sites of this segment that are discussed below.

Site 4 is located in segment II near Sanedra village. The GPR survey site was selected on the basis of field evidence of tectonic activities exposed in the excavated trenches by the local people for the mining purpose (Fig. 8.6). In the trench, a zone of various basaltic flows that were highly fractures and sheared (Fig. 8.6C) and intruded by dykes was identified. Because of the tectonic activity the rocks have been converted into the gouge like material. Due to high deformation and weathering, the original rock property was altered. This has been interpreted as the fault zone. With this background, the GPR survey conducted across the fault zone. Because of the requirement of good depth and resolution, radar profile conducted using 80 MHz antenna in bistatic mode.

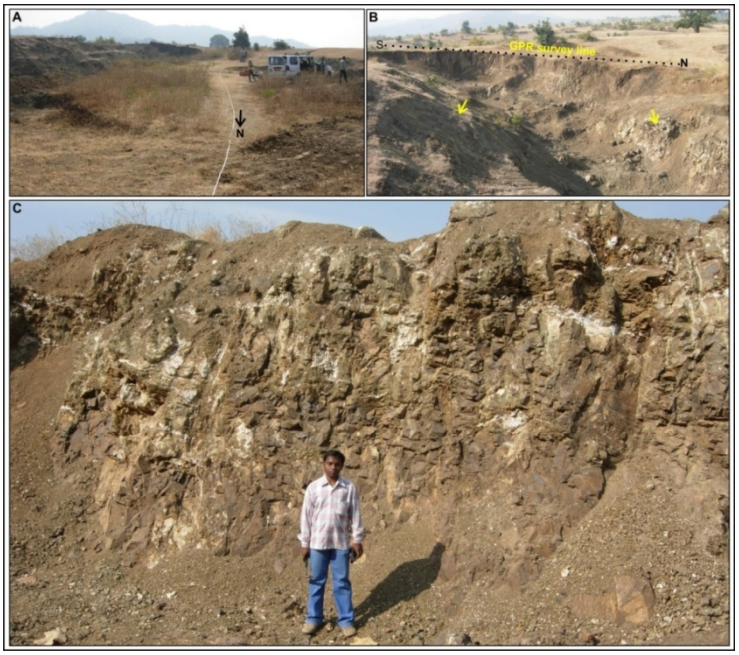

Figure 8.6 Field photographs of the GPR survey site 4 located near Sanedra. (A) Front view of site showing excavated trench in basaltic ridge and direction of survey line. Arrow indicated north direction. (B) Side view of survey site showing two different types of basaltic flows exposed in the trench, shown by the arrows. (C) A close view of the exposure showing highly fractures and sheared basalts.

On the basis of reflection pattern and amplitude, four different layers which related to four different basaltic flows were identified (Fig. 8.7). The upper layer from that ranges from 0 to ~ 3 m in depth is comprises of the reflections from the scree material. Below 3 m the other three layers comprises of radar reflections from various basaltic flows. This includes a layer of horizontal, parallel and high amplitude reflections that ranges from 3 to 5

m in depth. This layer is followed by radar facies that consists of low amplitude wavy reflections and ranges between 5 to 9 m. Below 9 m there is a thick layer of radar facies that have wavy nature and shows strong amplitude. The conspicuous feature is observed at 28 m along the distance (Fig. 8.7). At this point there is a visible brake in the continuity of the reflection pattern which throughout the depth of the profile. The close examination of the radar reflections suggests displacement along the vertical fault plane. This demarcates the NSF in the shallow subsurface according to which it is vertical at depth and becomes southward dipping reverse fault as it approaches the surface.

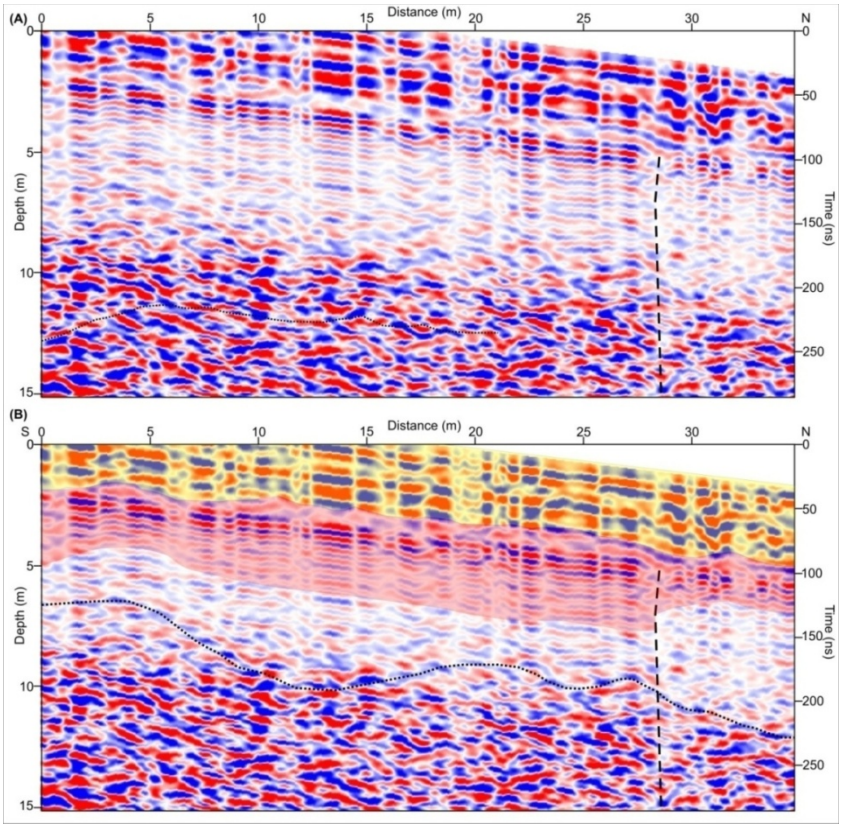

Figure 8.7 (A) GPR profile taken near Sanedra (site 4) using 80 MHz bistatic antenna. Note the discontinuity and displacement of the reflections at ~29m. **(B)** Interpreted section of the profile shown in A.

Site 5 is located at the left bank of the Nandikhadi River (looking towards downstream) near the Jhuna Ghanta village. This site has provided strong evidence of neotectonic activity in the field. The river has incised the basaltic terrain and produced deep narrow gorge like river valley. In the river valley, basaltic flows are exposed in the incised cliff sections along the river channel in the upstream area. The fault zone identified through the change in the rock properties and structure. In the fault zone area, rocks are highly fractured, sheared and weathered. The probable location of the NSF identified in the field within the fault zone area through the study structural characteristics. The intrusion of

quartz vein is noticeably increased in the fault zone area. And in the vicinity of NSF, these veins show displacement in a strike slip sense. The other conspicuous characteristic observed is the change in the dip of the basaltic flows in this zone. To the north of the main scarp the dip of the basaltic flows observed in the field is in north direction, while to the south of the scarp the flows are dipping southward. After the identification of the probable location of the NSF, GPR survey conducted few meters away in westward direction from the on the left bank side of the Nandikhadi River.

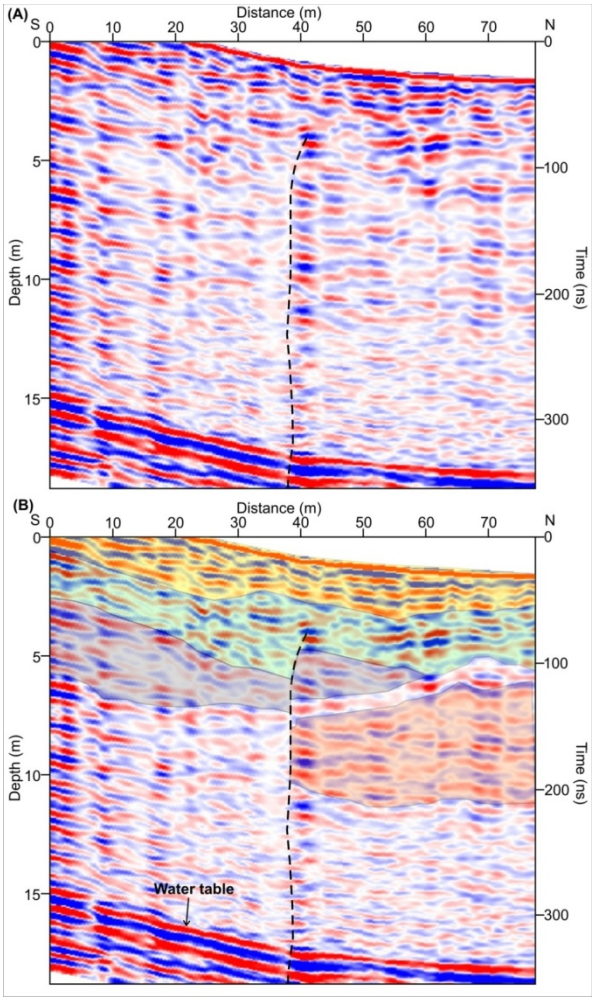

Figure 8.8 (A) GPR profile taken at Jhuna Ghanta (site 5) using 80 MHz bistatic antenna. Note displacement of the reflections at ~40 m. **(B)** Interpreted section of the profile shown in A.

The GPR survey carried out using 80 MHz bistatic antenna along the 75 m long survey line in the S-N direction. In the processed profile, five different radar facies identified on the basis of the change in the reflection pattern and amplitude (Fig. 8.8). The reflections in the upper most part of the profile from 0 to 1 m in a depth belong to thin alluvial cover. Below this, there is a layer of about 1 m thick comprises of horizontal reflections of high amplitude. This is followed by a layer of northward dipping reflections and comparatively of low amplitude. Below this, the profile shows two different types of

radar facies in the southern and northern part of the profile. The southern part of the profile comprises of very low amplitude horizontal to wavy reflections, while the northern part of the profile comprises of horizontal reflections of comparatively high amplitude (Fig. 8.8). This characteristic suggests contact of two different type basaltic flows that manifested in the GPR profile through sudden change in the reflection pattern and amplitude along the distance. The occurrence of such type of change is related to the fault activity. The closer examination of the upper part at 40 m along the distance of the profile indicates that the reflections of the upper layers are also displaced along the same plane that has made contact between two different flows (Fig. 8.8). This phenomenon marks the NSF in the subsurface. According to the nature of displacement observed in the processed profile, it has been interpreted that the NSF is vertical in the deep subsurface and becomes southward dipping reverse fault near the surface.

Site 6 is located near the Wali village. Prior to the GPR survey field studies carried out around the survey site to identify the fault zone and probable location of the NSF. Few meters eastward from the GPR survey site small stream has incised the basaltic terrain and provided good exposures in the cliff sections. The exposed cliff sections visited and studied along the length of the stream in the upstream area. The fault zone identified on the basis of the occurrence of sheared rocks and conspicuous structure alike the fault plane. The strike of the structure noted down and GPR survey carried out few meters away from the stream near the road side.

The GPR survey carried out using 80 MHz and 200MHz antenna. The 80 MHz antenna has provided good GPR profile which discussed here. The survey conducted over the S-N trending 50 m long survey line. In the processed profile, three types of radar facies identified that represent reflection from different types of host material (Fig. 8.9). The reflections from the upper layer that ranges from 0 to 1 m are from the artificially deposited scree material during the road construction. Below 1 m the radar facies comprises of northward dipping parallel reflections of high amplitude that continue up to the depth of ~ 5 m. Below 5 m there is a layer of comparatively low amplitude, parallel to wavy reflections dipping northward. In this particular layer discontinuity and displacement are seen at distance of ~ 29 m (Fig. 8.9). This is related to the tectonic movement along the vertical fault plane which is attributed to the NSF. Significantly, to the northern side of the fault plane reflection pattern and amplitude also changes. This could be related to the change in the physical and chemical properties of rock due to crushing and shearing that has resulted into the reflections of poor quality. Or this could be related to the contact between two

different flows. The tectonic movement has also displaced the water table which is very visible in the profile. Overall, it suggests the subsurface location of NSF that has displaced the rocks along the vertical fault plane.

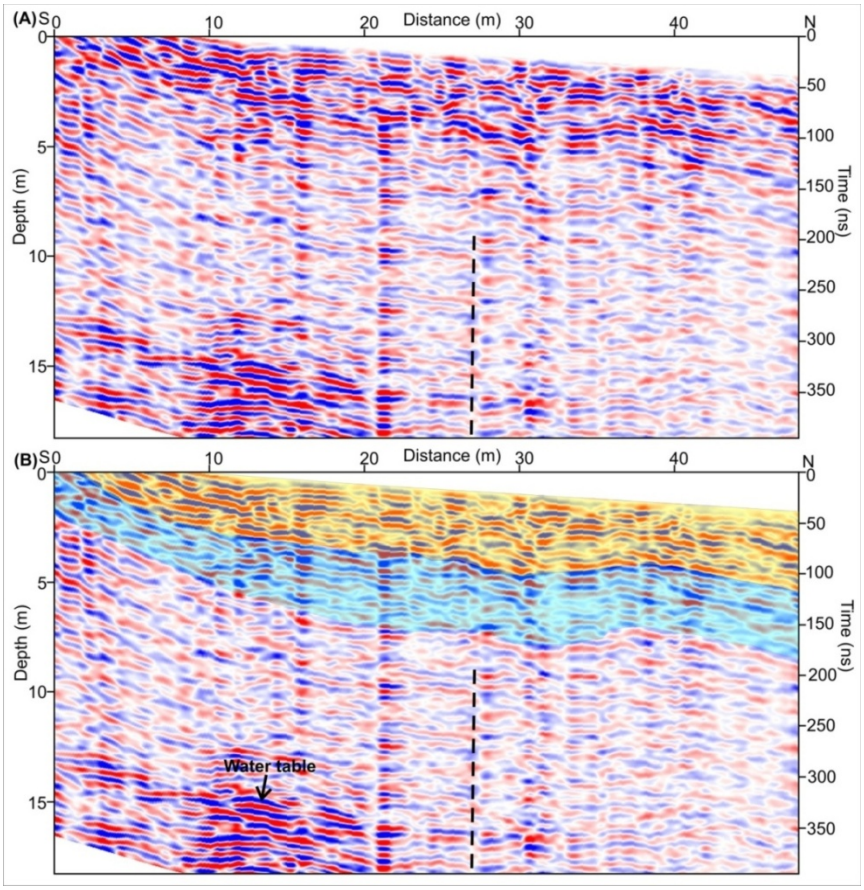

Figure 8.9 **(A)** GPR profile taken at Wali (site 6) using 80 MHz bistatic antenna. Note displacement of the reflections at ~ 29 m. **(B)** Interpreted section of the profile shown in A.

GPR studies in the Segment III

Site 7 is located in the segment III. The segment II is the smallest segment of the study area for which one GPR survey site was selected near the Kapat. The GPR survey site selected on the basis of the conspicuous morphotectonic setting. In the field NSF is expressed by steep scarp formed in the Deccan traps. In the vicinity of the scarp, the first order tributaries of the Madhumati River that emerging from the trappean uplands flow parallel to the mountain scarp in ENE-WSW direction. Although these streams are small and ephemeral, they show significant depth of the incision. The southward dipping basaltic flows are well exposed in the cliff section which visited all along the length of the channel in the upstream area. Accordingly, fault zone and the probable location of the NSF identified and GPR survey carried out.

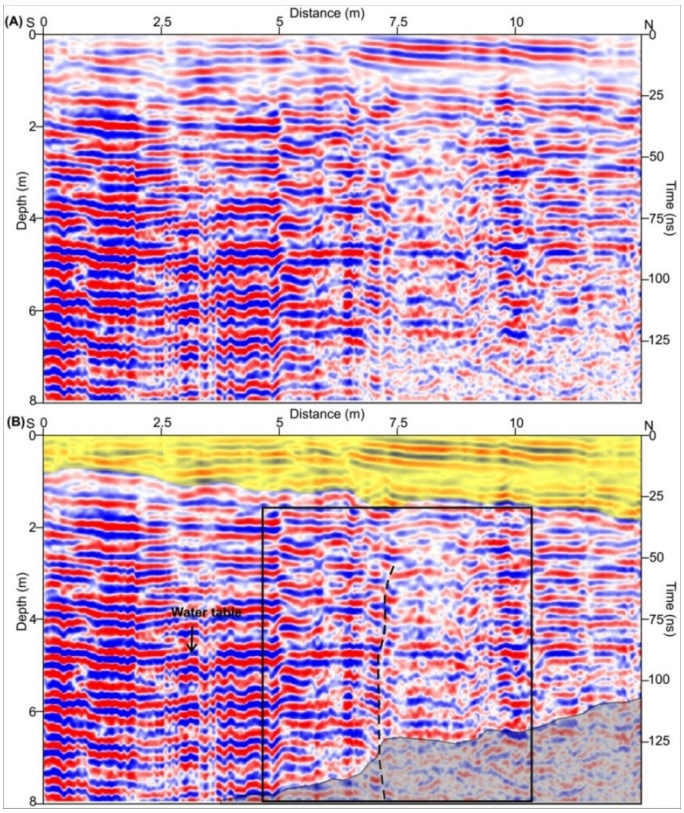

Figure 8.10 (A) GPR profile taken near Kapat (site 7) using 200 MHz monostatic antenna. Note displacement of the reflections at ~ 7.5 m. **(B)** Interpreted section of the profile shown in A.

The GPR survey carried out using 200 MHz antenna along the S-N oriented 12.5 m long survey line. The processed profile shows two different types of radar facies that represent two different rock properties (Fig. 8.10). The upper layer from 0 to 1 m shows horizontal and parallel reflections of high amplitude which represent thin alluvial cover. Below this, the profile comprises of the reflections from two different basaltic flows (Fig. 8.10). The southern part of the profile shows high amplitude horizontal reflections which continuous up t o 5 m distance. Beyond 5 m, the pattern and amplitude of the reflection changes and it sustain up to 10 m distance. This zone, from 5 to 10 m is the fault zone, comprises of complex pattern of low amplitude reflections which is related to the occurrence of numerous fractures and sheared rocks (Fig. 8.10). Within this zone, the major displacement observer at ~ 7.5 m distance which is attributed to the NSF. The closer examination of the behavior of the reflections suggests that the displacement is along the steeply southward dipping fault plane and shows reverse movement.

GPR studies in the Segment IV

In the segment IV, GPR surveys carried out at two locations which located near Jhagadia and Karad. In the eastern part and western part of the segment IV, NSF is geomorphologically expressed by the steep scarps formed in the Tertiary rocks and

palaeobank comprises of Pleistocene sediments respectively. Hence, one of the GPR survey site located to the northern limit of the Tertiary highland and the other site located over the Palaeobank of the Narmada River.

Site 8 is located near the Jhagadia village which in the eastern part of the segment IV of the study area. In this part, the NSF is expressed by trending steep scarp developed in the northern limb of the Jhagadia anticline. The Jhagadia anticline is 9 km long and 2 km wide asymmetrical anticline that extends between the Rajpardi and Jhagadia towns. It trends SW near Rajparadi and swings to a WSW trend near Jhagadia which is parallel to the trend of NSF. It plunges due WSW and faulted along the SSE limb. The core of the anticline comprises of the Tertiary conglomerates of the Babagura formation, overlain by Kand and Jhagadia formation consist of hard and compact calcareous bands. The northern limb of the Jhagadia anticline ends up abruptly.

GPR survey carried out using 200 MHz antenna along the N-S oriented survey line. There are three types of radar facies identified in the processed GPR profile (Fig. 8.11). In the profile, the radar facies from 0 to 1 m in depth belong to the reflections from the scree material as the survey site located near the road. Below the depth of 2 m the profile consists of two different radar facies. The northern part of the profile comprises of low amplitude wavy reflections from o to 17.5 m in distance. Beyond the distance of 17.5 m, the southern part of the profile shows high amplitude northward dipping reflections. There is an abrupt change in the pattern and amplitude of the radar facies at distance of 17.5 m (Fig. 8.11). This change could be related to the tectonic activity along the NSF. The type of the displacement observed through the pattern of the reflections suggests that the NSF is a steeply southward dipping reverse fault in this segment.

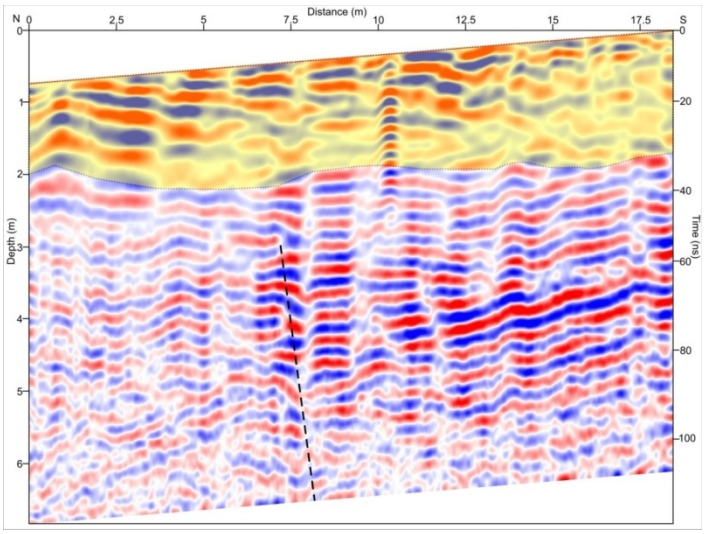

Figure 8.11 GPR profile taken near Jhagadia (site 8) using 200 MHz monostatic antenna. Note the significant displacement of the reflections at ~ 7.5 m.

Site 9 is located near the Karad. In this part of the segment IV, the NSF is expressed by ENE-WSW trending steep scarp formed in the Pleistocene sediments which is the Palaeobank of the Narmada River. The sediments of the Palaeobank comprises of loose sand, gravelly sand and silty sand. The previous studies suggest that the formation of the Palaeobank is related to the tectonic activity along the NSF that uplifted the surface and shifter the Narmada River northward which verified by the seismic survey (Agarwal, 1984). To know the shallow subsurface characteristics, the GPR survey carried out across the Palaeobank. Initially, GPR survey carried out using 200 MHz and 80 MHz antenna. Because the aim was to know the near surface nature of the NSF good resolution was required. The GPR profile that conducted using 80 MHz antenna has provided satisfactory result in term of resolution which discussed below.

The GPR survey carried out using 200 MHz antenna along the S-N oriented 35 m long survey line. In the processed GPR profile, three types of radar facies distinguished (Fig. 8.12). The upper part of the profile from 0 to 1 m depth comprises of wavy reflectors of high amplitude. This part represents the reflections from the scree material as the survey was conducted over the artificial track. Below 1 m the profile shows two different types of radar facies in the southern and northern part (Fig. 8.12). The southern part of the profile from the 0 to ~ 17.5 m comprises of wavy to horizontal reflections of high amplitude. While the northern part of the profile from 17.5 to 35 m comprises of discontinuous wavy reflections of very low amplitude. The sudden change in the amplitude and pattern of the radar facies related to the contact between two different lithologies. This is attributed to the tectonic movement along the NSF that has displaced two different types of lithology and created tectonic contact which is manifested in the GPR profile as the sudden change in the radar facies. On the basis of the behavior of the displaced reflections in the vicinity of the fault plane, it has been interpreted that in the shallow subsurface NSF is south dipping fault and has reverse type of nature.

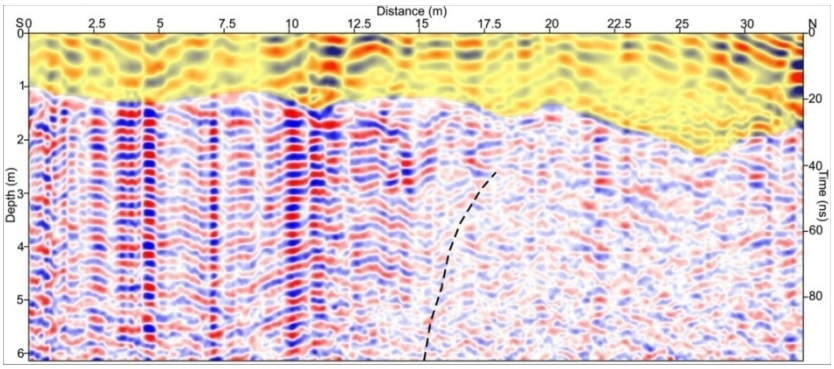

Figure 8.12 Interpreted GPR profile taken near Karad (site 10) using 200 MHz monostatic antenna. Note the sudden change in the radar facies at 15-17.5 m.

SHALLOW SUBSURFACE NATURE OF THE NSF

Overall, the results of the GPR survey suggest that the NSF is vertical at depth and becomes southward dipping reverse fault as it approaches the surface. However, at places NSF shows tectonic movement along the vertical fault plane. The change in the shallow subsurface nature of the NSF is discussed below segment wise.

In the segment I, GPR survey carried out at three locations near Gora colony (site 1), Umarwa (site 2) and Chakva (site 3) using 80 MHz antenna. The GPR profiles of site 1 and site 3 suggests that at deeper level NSF is vertical fault and shows, as the fault plane approaches the surface, it becomes of reverse nature and show displacement along steeply southward dipping fault plane. However, at site 2 of this segment, the NSF shows tectonic movement along the vertical fault plane.

In the segment II, the GPR survey conducted using 80 MHz antenna at three sites located near Sanedra (site 4), Jhuna Ghanta (site 5) and Wali (site 6). The interpreted GPR profiles of site 4 and site 5 indicates that the NSF is a vertical fault deep in the subsurface and becomes reverse as it approaches the surface. However, in the GPR profile of site 6, NSF has been interpreted hows displacement along the vertical fault plane.

In the segment III, GPR survey carried out near Kapat (site 7) using 200 MHz antenna. In the segment IV, GPR survey conducted near the Jhagadia (site 8) and Karad (site 9) using 200 MHz antenna. The processed GPR profile of these three sites suggest that the NSF is a vertical fault at deeper level and gradually becomes southward dipping reverse fault as it approaches the surface.

Overall, the interpretation of the GPR profiles indicates that in the shallow subsurface NSF becomes southward dipping reverse fault. The reverse nature and southern dip of the NSF could be explained by the influence of compressive stress regime prevailing in the study area due to continuous northward movement of the Indian plate. Basically, the origin of the NSF is related to rifting system and extensional regime, its behavior as the normal fault that shows displacement along the vertical fault plane is usual. After the final welding of the Indian plate with Eurasian palate there was compression which replaced the extensional system into compressive stress regime that resulted into the reverse nature of the NSF at shallow subsurface.