Need for initiating ground penetrating radar studies along active faults in India: An example from Kachchh


The landscape of India has been shaped by multicyclic tectonic movements along the various fault systems whose origin and subsequent tectonic history are related to the break-up and the northward drift of the Indian plate. Many of the faults are seismogenic and have a long history of tectonic reactivation and present some of the best examples of sedimentation in fault-controlled basins. It is imperative that detailed shallow subsurface studies are carried out along these faults to understand their nature, potential for stress accumulation and release, neotectonic evolution and palaeoseismic events. Apart from providing detailed field studies involving mapping of faults, geomorphic features and reconstruction of the stratigraphy of Quaternary sediments, the present article argues for extensive use of the Ground Penetrating Radar (GPR) primarily to delineate the subsurface geology along the various faults followed by trenching/excavation to reconstruct the neotectonic and palaeoseismic history. We briefly describe the salient features of GPR and also present as an example, the preliminary results of the first ever GPR surveys carried out by us along an active fault in Kachchh. GPR studies along the Katrol Hill Fault in Kachchh have helped in locating and understanding the nature of the fault and quantifying the amount of fault scarp retreat.

Neotectonic and palaeoseismic studies in India have received fresh impetus in the last one and a half decades due to the occurrence of devastating earthquakes mainly in the peninsular shield. The continued northward movement of the Indian plate is the main forcing mechanism which contributes to the neotectonic deformation and seismic instability of the Indian plate. The seismicity of Himalaya is considered to be of interplate type and is related to three active intrasutural boundary thrusts, namely the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Fault (HFF), whereas the neotectonics and seismicity of Stable Continental Region (SCR) is of intraplate type. Assessment of future seismic activity on the basis of historical records during the last 100–200 years is bound to leave several lacunae. Hence there is an urgent need to enlarge the database beyond historical records. Palaeoseismic events delineated so far (Table 1) are grossly inadequate to estimate recurrence interval of earthquakes or the nature of neotectonic activity along various faults. It is extremely important to understand the behaviour of various segments of the Indian plate in the recent past to the continued northward movement to properly appreciate the seismic risk. A detailed study on the documentation of the successive tectonic events along various fault systems and related landform development during Quaternary is essential. Information generated from state-of-the-art subsurface studies using Ground Penetrating Radar (GPR) will go a long way in rectifying this gap as far as the neotectonic and palaeoseismic history of India is concerned.

In this article we first briefly describe the basic elements and applications of GPR, a state-of-the-art geophysical technique for shallow subsurface studies, which has been proved to be extremely useful in carrying out similar studies in other parts of the globe. We then build up a case for initiating comprehensive geological studies in India along active faults using GPR, and present preliminary results of GPR studies carried out by us along the Katrol Hill Fault (KHF), a neotectonically and seismically active fault in the Kachchh region (Figure 1).

Ground Penetrating Radar

GPR is a general term applied to geophysical techniques which employ electromagnetic (EM) waves typically in the 1 to 1000 MHz frequency range to map structures and features buried in the ground. GPR studies are non-destructive
**Table 1.** Palaeoseismic events delineated so far in India (updated after Sukhija et al.\(^4\))

<table>
<thead>
<tr>
<th>Area</th>
<th>Evidence/source</th>
<th>Age of events</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Mahi valley, Mainland Gujarat</td>
<td>Soft sediment deformation includes liquefaction in mid-late Holocene terrace</td>
<td>3320 ± 90–2850 ± 90 yrs BP</td>
<td>36</td>
</tr>
<tr>
<td>Dhodhar valley, Mainland Gujarat</td>
<td>Soft sediment deformation including liquefaction in mid-late Holocene sediments</td>
<td>Younger than 5570 ± 30 yrs BP</td>
<td>37</td>
</tr>
<tr>
<td>Dholka, Mainland Gujarat</td>
<td>Liquefaction feature in a trench</td>
<td>2948 ± 295 yrs BP</td>
<td>38</td>
</tr>
<tr>
<td>Orsang valley, Mainland Gujarat</td>
<td>Soft sediment deformation, including liquefaction in mid-late Holocene sediments</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Great Rann of Kachchh</td>
<td>Soft sediment deformation and liquefaction</td>
<td>800–1000 yrs BP</td>
<td>39, 40</td>
</tr>
<tr>
<td>Great Rann of Kachchh</td>
<td>Soft sediment deformation and liquefaction</td>
<td>-2000 yrs BP</td>
<td>41</td>
</tr>
<tr>
<td>Bet Dwarka, Saurashtra</td>
<td>Sediment deformation and archaeological evidence</td>
<td>-1500 yrs BP</td>
<td>42</td>
</tr>
<tr>
<td>Ter (Killari/Latur), Maharashtra</td>
<td>Soft sediment deformation at different stratigraphic levels</td>
<td>Eight major seismic events</td>
<td>43, 44</td>
</tr>
<tr>
<td>Sumdo, Spiti valley</td>
<td>S1 and S2 – older than 90 ka</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shillong plateau, Assam</td>
<td>Soft sediment deformation liquefaction features</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Bihar</td>
<td>Palaeo liquefaction/deformation features</td>
<td>(i) Between 1700 and 5300 yrs BP</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ii) Older than 25,000 yrs BP</td>
<td></td>
</tr>
<tr>
<td>Shillong plateau, Assam</td>
<td>Deformed sediments, liquefaction</td>
<td>1200 ± 100 years BP</td>
<td>47</td>
</tr>
<tr>
<td>Trappean uplands, Maharashtra</td>
<td>Deformed sediments</td>
<td>5000–7000 yrs BP</td>
<td>48</td>
</tr>
<tr>
<td>Garhwal Himalaya</td>
<td>Sediment deformation</td>
<td>Holocene</td>
<td>49</td>
</tr>
<tr>
<td>Nainital, Kumaon Himalaya</td>
<td>Fault gouge and soils in landslide material</td>
<td>Neotectonic event, ca. 40–50 ka BP</td>
<td>50</td>
</tr>
</tbody>
</table>

Seismic events:
- 58–26 ± 4.3
- 56–37 ± 5
- 55–61 ± 10
- 53–90 ± 11

\( S_1 \) and \( S_2 \) – older than 90 ka

\( -600 \) yrs BP

\( -900 \) yrs BP

\( -1575 \) yrs BP

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**Figure 1.** a, Map of Mainland Kachchh showing the Katrol Hill Fault (KHF). Enclosed areas (squares) indicate the location of (b) and (c) (Inset) Location map. b, c, Map showing KHF and associated transverse faults (after Maurya et al.\(^10\)) and location of GPR profiles as dashed lines (not to scale) shown in Figures 4–6.

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subsurface investigations\(^\text{7}\) which provide high resolution profiles of depths up to 50 m. The radar produces a short burst of high frequency EM energy which is transmitted into the ground (Figure 2). Signals which are reflected back from within the ground are detected by a sensitive receiver, digitized and stored for post-survey processing, display and interpretation (Figure 2).

**Principle**

GPR surveys involve transmission of high frequency EM pulse of energy into the ground which radiates downward and at sediment interfaces some of the energy is reflected back to the surface\(^\text{5}\). The propagation of the radar signal depends on the electrical properties of the ground like relative permittivity (dielectric constant) and electrical conductivity\(^\text{5}\). Radar reflections are produced by changes in the electrical property associated with boundaries such as water table, stratigraphic units and lithological contacts\(^\text{5}\).

As with all other geophysical techniques, the most important step in GPR survey is to identify the problem. The target to be detected and the relative permittivity (dielectric constant) and electrical conductivity must be quantified as accurately as possible\(^\text{6}\). An important aspect of the survey design is to establish a survey grid and coordinate system. Survey line spacing is dictated by the degree of target variation in the trend direction. Generally, survey lines are run perpendicular to the trend of the feature under investigation in order to reduce the number of survey lines. The most common mode of GPR survey is common offset, single-fold reflection profiling. In such a reflection survey, a system with a fixed antennae geometry is transported along a survey line to map reflection versus position\(^\text{5}\). Various parameters that are to be defined in GPR surveys are the frequency, time window and sampling interval, station spacing, antennae spacing, line location and spacing, and antennae orientation\(^\text{5,8}\).

Selection of the operating frequency for a radar survey is not simple. Higher frequencies have shorter wavelengths which yield high resolution, while lower frequencies have longer wavelengths that yield greater depth of penetration but lower resolution\(^\text{5}\). There is usually a “trade-off” between spatial resolution, depth of penetration and system portability\(^\text{5}\). Most GPR systems employ separate antennas for transmitting and receiving (referred to as bistatic operation). Varying antennae spacing is a powerful aid in optimizing the system for specific types of target detection\(^\text{6}\). Increasing the antennae separation also increases the reflectivity of flatting planar targets, which can sometimes be advantageous\(^\text{5}\). In general, depth resolution of target increases as antennae separation increases.

**Advantages of GPR over other geophysical methods**

GPR is one important tool ideally suited for obtaining high resolution profiles of the ‘blind zone’ (~50 m depth), which otherwise is not possible by other geophysical methods\(^\text{6-8}\). GPR gives a more direct/realistic high-resolution image of the subsurface than other methods. 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 GPR allows selection of resolution with changing depth and is therefore ideal for neotectonic and palaeoseismic studies, where shallow depth but high-resolution images are required. The GPR can map subsurface layers (horizontal and inclined) with minor changes in electrical properties which other methods may fail to pick up\(^\text{6}\). The GPR can detect small structures, palaeo-liquefactions from the contrast between dielectrical permittivity of sand and clay, which is not possible by any other geophysical technique.

**Geological applications of GPR**

GPR is now widely used to image the subsurface and its demonstrated field of applications is manifold. It has been used in neotectonic, palaeoseismic and sedimentological studies in different parts of the world. Use of radio echo sounders to map the thickness of icesheets in the Arctic and Antarctic and permafrost soil applications\(^\text{5}\) are the most
successful early works in this area. Jol and Smith\textsuperscript{10}, and Van Overmeeren\textsuperscript{11} studied sedimentary features in various depositional environments using GPR. Lui et al.\textsuperscript{12} studied the groundwater flow pattern in fractured crystalline bedrock. Daniels et al.\textsuperscript{13} and Annan et al.\textsuperscript{14} observed the distribution and migration of subsurface liquid contaminants. Radar facies and sequences\textsuperscript{15,16} have been recognized and linked directly to sedimentological characteristics seen in cores and trenches. GPR studies carried out by Bridge et al.\textsuperscript{17} revealed more \textit{in situ} details particularly in delineating the lithofacies, geometry and orientation of large-scale inclined strata sets associated with channel bar migration and channel-filling. GPR surveys have been carried out on alluvial fan sediments\textsuperscript{18} mainly to characterize reflection patterns and to assess the potential of GPR in these deposits.

GPR studies have been conducted to detect near-surface Quaternary deformations, near-surface active faults in unconsolidated sediments, palaeoquakefaction and tectonic deformations, and earthquake subsidence events\textsuperscript{19-23}. Depth of water table and sedimentary facies which correspond to bars and channels are imaged by GPR which brings insight into recent fault activity\textsuperscript{20}. 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\textsuperscript{24}. It has been useful to delineate upward fault termination, colluvial wedges and sand injection, unconformities, reverse faults, fault-related fold, all indicating palaeoseismic activity. GPR has also been used in India for thickness measurement of Dokriani glacier in Garhwal Himalaya\textsuperscript{25}.

GPR is therefore ideally suited for detecting and imaging geological features between the surface and a depth of several tens of metres, to construct a complete picture of subsurface features caused by earthquakes and other tectonic events.

**Need for GPR-based fault studies in India**

The Indo-Gangetic plain, Gujarat alluvial plain and Kachchh basin with significant sedimentation during Quaternary times are ideally suited for GPR studies, which can help in delineating the neotectonic activity in a region. Neotectonic activity is amply testified by various geomorphic features, entrenched drainage, knickpoints, seismically induced soft sediment deformation, terraces, and current and historical seismicity\textsuperscript{26-29}. Moreover, several faults are known to be the potential source of earthquakes, viz. the boundary thrusts of the Himalayan region, the Narmada-Son Fault and the E-W trending faults of the Kachchh region\textsuperscript{30,31}. It is unfortunate that even the areas of high seismic risk have remained neglected in this respect. The region of Kachchh is a good example of this. The historical, instrumental and palaeoseismic data (Table 1) available so far are inadequate to precisely correlate the observed pattern of seismic activity with the known tectonic features. This is mainly due to the fact that neotectonic and palaeoseismic studies have been few, which can allow for identification of seismogenic faults and improved seismic risk evaluation. The following are some of the reasons to provide a major thrust to GPR-based fault studies in India.

(i) The geomorphic set-up and topography of the Indian plate is primarily influenced by tectonic movement along faults.
(ii) Quaternary sedimentation has been controlled by movements along faults, allowing documentation of recent tectonic and palaeoseismic activities.
(iii) Sediment exposures adjacent to faults are not enough for detailed stratigraphic and palaeoseismic studies.
(iv) Several earthquakes have occurred in historical times along several fault zones. These fault zones have been identified as zones of high seismic risk, but exact relationship of seismic phenomena with fault movements is not known.
(v) Past history (Late Quaternary) of tectonic and seismic events along these faults is not known.

Although neotectonic activity is recorded from the peninsula and extra-peninsula, these remain to be bracketed into distinct phases or events which can form a sound basis for evaluating the seismic potential of the various tectonic domains of the Indian plate. When the entire Indian plate is constantly on the move, it is illogical to assume that any part of it is tectonically stable. The entire plate has to be active, and the investigations should, therefore, focus on the response of the different parts of the plate to the ongoing movements and delineate the neotectonic history of each part or segment. It is therefore suggested that the future work should first deal with identification of seismogenic faults/active faults and then look for palaeoseismic features through trenching along such faults to know their past history\textsuperscript{3}. One major handicap in studying the Quaternary deposits of fault-controlled basins like the Ranns of Kachchh is the lack of exposures. The only way, therefore, to investigate these deposits is by carrying out state-of-the-art subsurface studies. GPR is one important tool ideally suited for such terrains. As shown in Figure 3, GPR can play a significant role in generating neotectonic and palaeoseismic data along active faults.

**GPR surveys along Katrol Hill Fault**

We present the preliminary results of GPR surveys carried out by us along the KHF in Kachchh (Figure 1). The KHF is a major E-W trending intrasubbasin fault located in the central part of Mainland Kachchh. The fault separates the Bhuj Formation to the north and the Jhirio and Junara formations to the south and is considered to be neotectonically and seismically active\textsuperscript{28,31}. The fault presents an impressive north-facing escarpment and exhibits various geomorphic features like undissected fault scarps, incised
drainages and sharp break in long profiles of streams crossing the KHF. All these features point to the active nature of the KHF\textsuperscript{29}. 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\textsuperscript{32}. The fault is not continuous as it is cut across by several NE–SW trending transverse faults (Figure 1 b, c) which have laterally displaced the E–W trending KHF at several places\textsuperscript{35}. The KHF therefore presents a complex tectonic and structural setting which needs to be understood to precisely delineate the nature of the neotectonic and seismic activity along this fault. Our present attempt has been limited to demonstrate the utility of GPR for precisely locating the faults and understand their near-surface structural characteristics.

We undertook GPR surveys using a GSSI SIR-20 system along three N–S oriented transects in three different segments of the KHF, with a view to precisely locate the fault plane/zone and also to determine the near-surface characteristics of the KHF. The profiles were obtained by dragging a shielded 200 MHz antennae along the measured survey lines. The fault was picked up 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 is the usual practice and requirement of the GPR surveys, the process was repeated several times until good quality data were obtained. The best profiles were processed to remove the spurious reflections due to surface objects (noise) and to enhance the quality of data before being interpreted. Identification of fault within the same lithology from GPR profiles is based on criteria like displacement of reflections, relative difference in amplitude of radar signals on either side of the fault and a drastic decrease in amplitude along the fault line, while the vertical and horizontal changes in lithology are identified based on texture, continuity and strength of the reflections\textsuperscript{34}.

The first profile, 200 m long, was taken north of the Khatrod scarp (Figure 4 a). In this profile, two faults have been identified (Figure 4 a). The KHF is reflected as a high angle, southward-dipping reverse fault up to a depth of \(~2.5\) m and continues further down as a vertical normal fault (Figure 4 b). The profile also shows extensive deformation in the thin-bedded limestones, shales and sandstones of Junara Formation to the south of the fault. The sandstones of the Bhuj Formation to the north of the fault plane also show deformation, which is restricted to a narrow zone of \(~50\) m adjacent to the fault (Figure 4 a). The second fault, further north in the profile dips towards north and is a smaller-scale sympathetic fault parallel to the KHF within...
the Bhuj Formation (Figure 4c). The profile shows that the KHF is a high angle reverse fault near the surface which becomes vertical at depth (Figure 4b). The GPR profile revealed that the KHF is located about 800 m towards north from the base of the Khatrod scarp (Figure 4d). 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 (Figure 4d).

The second profile was taken near Gangeshwar located to the south of Madhapar village (Figures 1 and 5a). The profile shows the KHF as a southward-dipping, high-angle reverse fault and is easily picked up by the sharp lithological contrast reflected in the profile up to a depth of about 6 m, beyond which there is significant attenuation of radar signals (Figure 5b). The limestones and shales of the Jumara Formation to the south of the fault show extreme defor-
Figure 5.  

- **a.** 200 m long processed profile taken north of Gangeshwar. For location, see Figure 1 c.  
- **b.** Enlarged view of the portion marked in showing the KHF.  
- **c.** Geological section interpreted from the profile.
mation as tight folds and upward dragging of the strata due to movement along the KHF (Figure 5 b, c). The sandstones of the Bhuj Formation to the north of the fault plane show little or no deformation (Figure 5 b). Interestingly, at this place, the fault plane was located just ~50 m north of the fault scarp. The scarp retreat therefore at this place is much less.

We also carried out a 3D GPR survey across the KHF in addition to the 2D profiles at a site located ~5 km south of Mirijapur on the Bhuj–Mandvi road (Figure 6). The method for generating a 3D profile of the subsurface is different from that adopted for 2D profiles. First, the exact location of the KHF was demarcated by 2D GPR surveys (Figure 6 a). A block of 10 × 10 m located right over the fault was selected for generating 3D data. The area selected was divided into grids of 1 × 1 m by marking the survey lines 1 m apart, both across and along. The 200 MHz antenna was moved along each survey line marked within the selected block. The data show the KHF as a south-dipping, high-angle reverse fault (Figure 6 b, c). This shows that with the help of GPR, it is possible to detect a 3D fault pattern and resolve doubts about changes in fault dips.

Results of the preliminary GPR studies suggest that the KHF is possibly a south-dipping, near-vertical reverse fault which extends as a vertical normal fault further in the subsurface. The fault originated as a near vertical fault in extensional regime during the rifting phase of the Kachchh basin[16]. Subsequently, the KHF along with other E-W trending master faults has been involved in several episodes of basement uplift due to inversion since the Late Cretaceous[11,31]. The change in the nature of the fault plane with depth may be attributed to changes in the tectonic stresses during the

Figure 6. a, 30 m long GPR profile obtained south of Mirijapur village along Bhuj–Mandvi road showing the KHF. b, c, 3D GPR data showing the KHF.
inversion phase of the basin. The general reverse nature of the fault in the shallow subsurface indicates neotectonic activity mainly under compressive stress conditions. 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. Detailed GPR studies along several other transects are essential to confirm the preliminary findings of this study. The GPR data need to be further substantiated by detailed trenching studies. The transverse faults are also to be investigated to understand their influence on the structural characteristics of the KHF. However, the study amply demonstrates the utility of GPR as a powerful tool for detailed fault mapping and precisely locating the trenches for neotectonic and palaeoseismic studies.

Conclusion

In this article, we have attempted to highlight the unique features and capabilities of the GPR, which provides an invaluable tool to take up detailed shallow subsurface studies along active faults. Our preliminary results of GPR surveys point to the usefulness of GPR in fault studies, which are extremely important to generate vital data to understand the neotectonic and seismotectonic characteristics of the Indian plate. The study also demonstrates the utility of GPR to precisely locate faults where there is no geomorphic expression, which is essential for the selection of sites for palaeoseismic investigations. We believe that GPR studies combined with field mapping and trench studies along various faults should be initiated in the country to generate data on their neotectonic and palaeoseismic aspects.

GENERAL ARTICLES


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