GEOLOGICAL CHARACTERISATION OF THE KATROL HILL FAULT AS A POTENTIAL SEISMIC SOURCE AND ITS IMPLICATION FOR EARTHQUAKE HAZARD SCENARIO IN KACHCHH, WESTERN INDIA

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INTRODUCTION

The intra-plate Kachchh paleo-rift basin, located at the western continental margin of the Indian plate, is characterized by multiple seismic sources. This is evidenced by the spread of historic and current seismic activity along the E-W trending intra-basin fault systems. Available fault plane solutions of high to low magnitude earthquakes suggest reverse dip slip with strike-slip component under compression. Since the last high magnitude 2001 Bhuj earthquake (M_w 7.7) and the prolonged aftershock sequence, the eastern part of the Kachchh basin is identified as the Kachchh Seismic Zone that encloses the Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and the Island Belt Fault (IBF). The present study is concerned with the Katrol Hill Fault (KHF), which does not show significant historical seismicity apart from very few low magnitude shocks. In such a scenario it is likely that the KHF may be underestimated as a credible potential seismic source in the region, which usually happens with faults that have longer periods of quiescence.

The Katrol Hill Fault (KHF) is characterized by a very limited number of instrumental seismology data, including focal solutions along it with apparent low magnitude earthquakes and low-level seismicity, which could be another reason for its underestimation as a potential seismic source. However, neotectonic studies along the KHF have shown that it has produced three Late Quaternary surface faulting events in the past ~30 ka B.P., which means that the estimation of surface rupture hazard and its seismogenic potential is imperative. Thus, in the present study, the lateral extent of Late Quaternary surface faulting along the KHF and their magnitude (M_w) are estimated using various empirical relationships. Further, geomorphic effects of surface faulting events as observed in the Gunawari and Gangeshwar river basin in the form of drainage reorganization are described. Implication of surface rupture hazard by evaluating seismogenic potential of KHF using geological methods provides critical data for civil engineering design as well as seismic hazard estimation and mitigation.

METHODOLOGY

A largely rocky landscape coupled with a lack of good complete sections, except the Khari river section, meant that the tracing of Late Quaternary surface faulting along KHF could not be done using routine field mapping alone. In view of this, the approach and methodology applied in the present study were largely governed by the area-specific conditions. An interdisciplinary strategy that used field mapping, shallow geophysical studies using GPR, microscopic studies using optical microscopy and Scanning Electron microscopy (SEM) was followed. Detailed field investigations were carried out to map the Quaternary deposits in the area and samples were collected from the Quaternary deposits found in the KHF zone for analyses under the optical microscopy and Scanning Electron Microscopy (SEM) to examine the presence of microtextures related to coseismic faulting processes and to precisely locate the surface rupture trace of the KHF. The field investigation was also accompanied by shallow subsurface geophysical surveys with Ground Penetrating Radar (GPR) and data was acquired in the form of two-dimensional (2D) profiles along transects overlain by Late Quaternary deposits concealing the surface trace of KHF. The parameters such as surface rupture length, displacement and slip rate derived from the above-mentioned analyses were used to estimate the magnitude of paleo-earthquake along the KHF using various empirical relationships. The presence of buried paleo-valley and the wind gap which resulted due to surface faulting along KHF in the Gunawari and Gangeshwar river basins was also established using the GPR studies assisted by geomorphic cross-sections, longitudinal river profiles, morphometric parameters and Chi (χ) analysis.

LATE QUATERNARY SEDIMENTS IN THE KATROL HILL FAULT ZONE

At many places along its length, the KHF is buried under thin and patchy cover of Late Quaternary sediments. Sporadic occurrences of Quaternary sediments in the Katrol Hill Range (KHR) comprise of boulder colluvium at the base, overlain successively by aeolian miliolite, valley-fill/ fluvial miliolite (reworked), sandy alluvium and scarp derived colluvium. The bouldery colluvium deposits found overlying the Mesozoic rocks at the basement are degraded debris derived from the scarps and are poorly sorted comprising angular to sub-rounded boulders, cobbles, pebbles and fine sand, derived from the formations consisting of shales, sandstones and siltstones. The overlying aeolian and valley-fill or fluvially reworked miliolites are the most commonly encountered varieties of miliolites.

The term miliolite is applied to Late Quaternary lithified carbonate-rich sediments of aeolian origin that were blown off from the coastlines to far inland areas where they were accumulated in depressions and against obstacles. Scattered occurrences of miliolites in Kachchh are reported from a wide variety of geomorphic settings that include hill slopes, valleys and depressions, wind gaps and ravines. The aeolian miliolites were deposited as obstacle dunes in front of the scarps burying the KHF partially and also in valleys within the hilly terrain of KHR. Some parts of these deposits have been reworked by stream action forming valley fill miliolites, which are readily distinguished in the field by horizontal stratification and presence of pebbles and boulders of Mesozoic rocks.

Available U/Th chronological data show that the aeolian miliolite deposition in KHF zone spanned the Late Pleistocene up to ~42 ka B.P. The stratigraphically younger fluvial deposits, dated by OSL technique in the Khari river section date back to ~32 ka B.P. Based on literature, three Late Quaternary surface faulting events are identified from the most well exposed Khari river section. OSL dating of the Khari river section show that the Late Quaternary surface faulting events occurred around 31.8 ka B.P., 28.5 ka B.P. and 3 ka B.P. These ages are in agreement with the U/Th dates on aeolian miliolites which suggest deposition up to ~42 ka B.P.

FIELD EVIDENCE OF LATE QUATERNARY SURFACE FAULTING

The field evidence of surface faulting is observed in the form of offsetting of Late Quaternary sediments overlying the KHF trace. The best exposed section is located ~ 5 km SSW of Bhuj, the cliff section comprises stratified Late Quaternary sediments unconformably overlying the KHF fault trace exposed in Mesozoic rocks at the base. The sediments consist of colluvium (Unit 1) at the base followed by gravelly sand (Unit 2 and 4) with an intervening lensoid layer of finely laminated sand (Unit 3), stratified miliolitic sand (Unit 5) and scarp derived colluvium (Unit 6) at the top. All units show erosional bases. The entire section shows offsetting due to reverse faulting along two faults that converge and join up at the base with the KHF fault trace within the Mesozoic rocks. OSL dating of this section shows that the three events occurred at 31.8 ±2.8 ka (Event 1-oldest), 28.5 ±3.7 ka (Event 2) and 3.0 ±0.3 ka B.P. (Event 3-youngest).

Three surface faulting events were identified based on offsetting of stratigraphic units. During each of the three faulting events, the KHF displaced the then existing topographic surface as it propagated upwards in the thin sediment cover after each surface faulting event. The post-faulting erosion was more severe on the southern uplifted block compared to the footwall which has preserved larger thickness of sediments. Event 1 post-dates the deposition of Unit 1 during which KHF bifurcated into two faults (F1 and F2) due to rheological change as it propagated upwards from hard and compact Mesozoic rocks to unconsolidated colluvial sediments above which produced a displacement of ~3.5m. Erosion of the scarp formed during Event 1 precluded deposition of Units 2, 3 and 4. Unit 2 and 4 comprise gravelly sand with a lensoid body of finely laminated sand. Event 2 occurred after the deposition of Unit 4 which resulted in upward propagation of both F1 and F2. The wedge-formed between these two fault planes shows evidence of severe deformation like deformed stratification and sympathetic micro-faults with offset laminations along the fault planes.

Event 2 with a displacement of 2.2m was followed by erosion of the offset topography and deposition of stratified miliolitic sand (Unit 5) and scarp derived colluvium (Unit 6). Unit 5 is not observed in the southern uplifted block as, either it was not deposited in the uplifted block or it was eroded off before the deposition of scarp derived colluvium (Unit 6). Offsetting of Unit 6 along F1 and F2 indicates that Event 3 displaying ~2.2m of offset occurred after its deposition. A minimum cumulative displacement of ~8 m is estimated based on the offset stratigraphy. Based on available optically stimulated luminescence (OSL) dating of this section, the three events identified are younger than 31.8 ±2.8 ka (Event 1), 28.5 ±3.7 ka (Event 2) and 3.0 ±0.3 ka BP (Event 3).

The Quaternary deposits in the Khari river section showed displacement of 3.5m, 2.2m and 2.3m for the oldest, intermediate and youngest event of surface faulting. The slip rates of 0.66 mm/yr and 0.09 mm/yr were associated with the three events of surface faulting which was calculated using the slip history diagram.

Another exposure of deformed Late Quaternary sediments is located to the south of Bharasar village, where a NE flowing lower-order tributary of Khari river shows incised Late Quaternary deposits on its eastern bank. This site is located ~3 km west to the above described Khari river cliff section. The older fault plane of the KHF within the Mesozoic rocks (lithotectonic contact between Bhuj and pre-Bhuj formations) is exposed across the stream bed, which is unconformably overlain by 4-5 m thick Late Quaternary sediments. The horizontally stratified layers of gravelly sand unit are truncated along a gently southward dipping fault plane in a reverse manner. Downward extension of this plane correlates with the KHF fault plane in the Mesozoic rocks exposed in the river bed.

To the south of Bhujodi, exposure of aeolian origin miliolite deposits are found in a shallow depression in front of the scarps effectively burying the KHF fault plane. The fault line of the KHF is concealed below the miliolite deposits. The aeolian characteristics of the deposit are evidenced by the large scale dunal cross-bedding of well-sorted fine grain miliolitic sand. Above the buried fault line of KHF, an E-W trending, couple of meter wide zone showing high degree of deformation in which the dip of the foresets of thinly-laminated aeolian origin cross-bedded miliolite strata are showing near vertical dips. This zone of deformation is laterally traceable throughout the outcrop along the buried fault trace of KHF and evident of post miliolite phase of neotectonic reactivation. Away from the KHF, the foresets attain gentle northward dips within a few tens of meters.

GROUND PENETRATING RADAR STUDIES

GPR has been shown to successfully investigate the geological properties of the shallow subsurface by detecting changes in the physical character of the subsurface commonly associated with geological features in the form of radar reflections caused by contrasts in the dielectric properties of adjacent materials. For the characterization of the Quaternary sediments found in the KHF zone, GPR surveys were carried out in the regions showing the presence of miliolite outcrops for radar characterization of sediments and sediments overlapping the fault line to interpret the signatures of faulting in Late Quaternary sediments. Consequently, the GPR survey revealed the presence of wind gap and a buried paleo-valley in the Gunawari river basin. Additionally, GPR surveys were carried out at Bharasar, Tapkeshwari, Bhujodi and Ler areas along N-S transects over the KHF zone with Quaternary sediment cover and evidence of deformation to identify the precise location of KHF in the subsurface and its upward extension into the Quaternary sediments. The sites for GPR data acquisition were selected based on neotectonic and geomorphic mapping of the KHF through and beyond the zones of observed fault exposures and DEM analysis. The processed GPR data of the four above mentioned locations along the KHF zone shows high amplitude, continuous reflectors which characterize the Quaternary sediments. These reflectors occur up to a depth of ~3-5m, which marks the Quaternary-Mesozoic interface marked by differences in reflection strength, geometry and amplitude contrast in the radargram. The Mesozoic rocks in the radargrams are characterized by moderate-low amplitude, dis-continuous reflectors. The fault plane of KHF is observed as plane truncating and offsetting reflectors found in the Mesozoic rocks and continuing through the Quaternary-Mesozoic interface into the overlying Quaternary sediments. Abrupt changes in amplitude strength, signal scattering and reflection pattern observed across the fault plane corresponds to lithological variations. The different features related to aeolian and reworked miliolite deposits are interpreted on the basis of differences in reflector geometries and patterns. The radargram of all four sites clearly indicate the presence of tectonically induced deformation features and location of the KHF in the subsurface.

MICROSCOPIC EVIDENCE OF LATE QUATERNARY SURFACE FAULTING

The results from GPR data helped in selecting precise locations for the collection of samples for petrographic and SEM studies. Samples from Late Quaternary miliolite deposits were collected from near or exactly on the KHF zone to identify microscopic evidence of faulting. For comparison purposes, the miliolite deposits lying away from the KHF zone were also analysed. The GPR results are supplemented by microscopic analyses such as petrography and SEM of Late Quaternary deposits exposed along the KHF in order to establish the continuity of surficial deformation by observing the microscopic signatures of tectonic deformation. Thus, the microscopic studies were carried out to further confirm and precisely estimate the length of Late Quaternary surface faulting along the KHF.

The petrography of the samples collected from along the KHF zone showed micro-fracturing and recrystallization of the quartz grains and peloid bioclasts with presence of calcitic microfibers on their periphery. They also showed slight orientation of the constituent mineral grains and undulose extinction of quartz grains.

The SEM microtextures such as intensive breakage, adhering particles, striations, exfoliation marks, rolled and euhedral quartz grains were displayed by the quartz grains separated from the samples located along the KHF zone; while those located away from the KHF zone did not show presence of any of the above listed features related to tectonic deformation. They showed only fluvial microtextures with solution action and silica precipitation features. Based on the evidences of Quaternary deformation using these studies, it is inferred that of the total ~70 km length of the KHF, at least 21 km of it in the central part ruptured during the three surface faulting events during the Late Quaternary. The rest of the part of KHF did not rupture as indicated by the absence of Quaternary sediment deformation.

ESTIMATION OF SEISMOGENIC POTENTIAL OF KHF

Various empirical equations derived from scaling relationships directly relate the fault parameters such as fault surface and sub-surface rupture length, fault rupture area, displacement, seismic moment and slip-rate to the earthquake magnitude. The present study has been able to estimate these parameters with respect to the three Late Quaternary surface faulting events as observed in the Khari river section. The slip rates, displacements and chronology are derived from the Khari river section using the slip history diagram while, for delineating the length of KHF affected by surface faulting field mapping, GPR survey and microscopic analysis (petrography and quartz surface textures using SEM) of sediments overlying the KHF were carried out. The estimated length, displacement and slip-rate of Late Quaternary surface faulting were used in the regression equations to calculate magnitude of surface faulting events.

Based on length of surface rupture

For a given rupture length, the empirical relationships between earthquake magnitude and fault rupture length, allow an average magnitude to be selected. Assuming that a fraction of total fault length will rupture during an earthquake, a relationship between the rupture length and magnitude for a reverse fault is derived as-

$$Ms = 2.021 + 1.142 \log L \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where, L is the rupture length in meters

Substituting the value of L in the above equation with 21000 mm in equation (1), the final value of Ms was 6.9.

The surface wave magnitude (Ms) was converted into moment magnitude (M_w) as the latter is a widely accepted parameter for earthquake magnitude. The empirical conversion relation for $M_s \geq 5.5$ is given as-

$$M_w = 0.8126 (\pm 0.034602) M_s + 1.1723 (\pm 0.208173) \quad . \quad . \quad (2)$$

Using the above conversion equation and substituting the Ms values of earthquake magnitude obtained, the value of moment magnitude (M_w) was obtained as 6.7 $\pm$0.44.

Another empirical equation used to estimate magnitude using surface rupture length is-

$$M = a + b * \log (SRL) \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where, a and b are constants with values 5.08 and 1.16 respectively and SRL is the surface rupture length in kilometre.

This equation has yielded moment magnitude (M_w) of 6.6 using the fault surface rupture length value of 21 kms.

Based on displacement

The values of 2.3, 2.2 and 3.5 were obtained for displacement and 0.66 and 0.09 were slip-rate values of the three events of surface faulting obtained from the Khari river section. Using the above information, the magnitude of surface faulting was calculated using a relation given as-

$$Ms = 6.793 + 1.306 \log D \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Using the above equation and substituting the displacement values- 3.5 m (Event 1), 2.2 m (Event 2) and 2.3 m (Event 3) yielded the Ms values 7.4, 7.2 and 7.2 respectively.

The surface wave magnitude (Ms) is converted into moment magnitude (M_w) using the equation (2) and the moment magnitude M_w 7.1 $\pm$0.45, 7.0 $\pm$0.44 and 7.0 $\pm$0.44 for three surface faulting events along the KHF were obtained.

Another empirical relationship involving displacement and moment magnitude is-

$$M_w = a + b * \log (MD) \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Incorporating the value of maximum displacement in the above equation yields M_w 7.08, 6.9 and 6.9 for events 1 (oldest), 2 and 3 (youngest) respectively.

Based on length of surface rupture and slip rate

An equation for regression of moment magnitude (M_w) as a function of fault rupture length (L) and fault slip rate (S) was formulated as-

$$M_w = A + B \log L + C \log S \qquad . \qquad . \qquad . \qquad . \qquad . \qquad (6)$$

Substituting the values of surface rupture length (L) as 21 km and slip rate (S) for individual events of Quaternary faulting in equation (6) yielded the value of 6.8 $\pm$0.25 for Event 2 which took place in early Holocene showing the slip rate of 0.66 mm/year and for the youngest (Event 3) which took place in late Holocene with a slip rate of 0.09 mm/year, provides M_w values of 6.6 $\pm$0.21.

The M_w values obtained from different equations as mentioned above, are remarkably consistent. The M_w values of the surface faulting events are minimum as the displacement measured is also minimum considering the highly eroded nature of the Quaternary sediments in the KHF zone. This is also implied from the fact that all major horizons displaced during surface faulting events show erosive contacts.

SURFACE FAULTING INDUCED DRAINAGE REORGANIZATION

Drainage patterns have a tendency to get preserved once established, so they incorporate noteworthy information about the past and present tectonic regime. In the present study, drainage realignment on a sub basin-scale as a consequence of tectonic tilting caused by multiple events of surface faulting along the range bounding the KHF during the last ~30 ka B.P. described in the small drainage basins of the Gunawari and Gangeshwar rivers that show highly anomalous channel characteristics. It is shown that the nature of tectonic activity can influence the simultaneous occurrence of well-known mechanisms of drainage realignment and formation of related landforms even in drainage basins of spatially-limited scale.

Gunawari and Gangeshwar river basins

The majority of the area of Gunawari basin lies in the Katrol Hill Range (KHR), located ~8 km upstream of its confluence with the Dharawa river. The Gunawari river basin has two asymmetrical domes named Ler (towards east) and Gangeshwar (towards west), as the northern limbs have steep dips (~60°-80°) while the southern limbs have moderate dips (~25°-35°) that progressively become gentle up to ~5° towards south. The Ler dome largely exposes the Jumara Formation while the Gangeshwar dome comprises of the younger Jhuran Formation. The eastward flowing Gunawari river swerves around the Ler dome to flow northward along the saddle at its eastern margin. Between the Ler and Gangeshwar domes is a buried paleo-valley filled by Late Quaternary miliolite deposits that is presently drained by the narrow and incised channel of the Gangeshwar river. The paleo-valley extends southwards into the wind gap which is also filled by miliolite deposits. The term ‘wind gap’ is defined as fragment of an abandoned channel that is filled with sediments of mainly fluvial origin.

Three topographic profiles oriented in N-S, NE-SW and E-W directions drawn from the Survey of India topographical maps to 1:50,000 scale, illustrate a strong influence of structure on the geomorphic set up of the Gunawari basin.

MECHANISM OF DRAINAGE REORGANIZATION

The present study shows that the restructuring and rearrangement of the drainage divides of the paleo-Gangeshwar and paleo-Gunawari river basins occurred through multiple processes of drainage realignment induced by tectonic tilting in the last ~30 ka B.P. The major events of drainage readjustment and realignment include formation of ‘V’ and ‘S’-shaped bends, abandonment of buried paleo-valley by river diversion, beheading of paleo-Gangeshwar river and westward directed headward erosion of the paleo- Gunawari river in the saddle zone to the east of Ler dome.

The occurrence of multiple (three) co-seismic surface faulting events in last ~30 ka B.P. was shown by previous and present field and GPR data of offset aeolian miliolite sediments over the KHF caused uplift accompanied by southward tilting of the Katrol Hill Range triggering the phase of drainage of rearrangement. The rearrangement of drainage lines occurred both by top-down and bottom-up processes and involved carving of new channels dominantly controlled by E-W trending strike of Mesozoic rocks with anomalous ‘V’ and ‘S’-shaped bends. Upliftment of the wind gap and paleo-valley due to southward tilting of Katrol Hill Range led to the beheading of the paleo-Gangeshwar river as it was cut off from its catchment in the south. Inability of the river to flow northward through the wind gap and paleo-valley located in the up-tilt direction resulted in the formation of ‘V’-shaped bend and the straight eastward channel up to ‘S’-shaped bend by forward erosion i.e., top-down process. The ‘S’-shaped bend was formed as this channel met with the channel of paleo-Gunawari river advancing westward by headward erosion i.e., bottom-up process. The present study suggests that the absolute influence of tectonic factors on the complex processes of drainage rearrangement are more explicit for younger and shorter timescales than geologically older drainage adjustments interpreted for regional and continental scales involving longer time periods.

IMPLICATION FOR EARTHQUAKE HAZARD IN KACHCHH

The identification and characterization of active faults as earthquake sources are essential parts of seismic hazard evaluation because they enable forecasts to be made of locations, recurrence intervals and sizes of future large earthquakes. Large magnitude surface rupturing events are expected along the KHF at the scale of few thousands of years, making it the only fault in Kachchh with an unusually long recurrence interval. There are temporal variations in recurrence intervals of great earthquakes on a larger time scale. Therefore, the seismicity along KHF does not follow a following a normal seismic cycle. Because the strong ground motion travels large distances and thus impacts larger areas, there is need to understand direct impact of surface rupture induced ground deformation that tends to affect the structures on or close to the trace of the fault. The analogous reverse faulting earthquakes in recent times, El Asnam 1980, Sahellgiers 1989 and the Mascara 1994, reinforce the idea that surface faulting in the KHF is a potential source of future large earthquakes.

The seismic hazard analysis attempts to deliver better results for developing advanced building codes by correlating a multitude of data. In order to achieve this, the development of models based on fault parameters data, which is entirely based on geological evidences poses as a significant task to be accomplished. For achieving this, different methods which impart long-term and comprehensive paleoseismic records, as provided by fault rocks studies and geochronologic data, are required which incorporate multi-proxy evidences. At this point, the geological methods for overcoming the above specified tasks, which involve the use of detailed paleoseismic data such as information related to the magnitudes, locations, and types of earthquakes associated with long recurrence intervals (~ thousands of years) can provide information that is largely absent from most historical, geodetic, or seismicity records (~ tens to hundreds of years). Such information forms an essential part of any seismic hazard assessment process and can be assessed by employing various geological and geomorphological techniques. The information provided by the geologic and geomorphologic analysis is used to develop earthquake models which delivers important knowledge about the location, dynamics and geometry of active faults; estimates of former fault rupture magnitude and its timing of occurrence.

CONCLUSIONS

The Katrol Hill Fault (KHF) strikes E-W and is structurally expressed as a high angle, south dipping, range bounding reverse fault in Central Mainland Kachchh. The fault that marks the lithotectonic contact between the Bhuj Formation to the north and Jumara and Jhuran

Formations to the south. The KHF is marked by discontinuous and sparse occurrences of different varieties of Late Quaternary deposits, of which, the aeolian miliolites and valley-fill or fluvially reworked miliolites are the most common type found on both the windward and leeward slopes of the north facing scarps towards the southern side of the KHF and in the valleys and depressions respectively, present in the KHR. The thin sections analysis of fluvial and aeolian miliolites observed under optical/petrological microscope show faulting-related microfeatures such as microcracks along the grain boundaries of detrital mineral grains and prominent breakage and fracturing of peloid bioclasts, shape-preferred or crystallographic orientation among the elongated allochems and detrital mineral grains, formation of macro-sparite by recrystallization of calcitic cement and detrital quartz grains and occurrence of polycrystallinity of quartz grains. The quartz grains from fluvial and aeolian miliolites samples collected from the KHF zone observed using SEM displayed the microtextures such as striation, exfoliation, fresh fractured surfaces, rolled and euhedral quartz grains and adhering particles in addition to the extremely broken and fractured grain surfaces. All the above-mentioned microtextures found in the quartz grain samples collected from the fault zone can be attributed to the neotectonic processes/surface faulting, as these are not observed in the samples collected from the locations away from the fault zone. Previous and present study shows that the sediments were offset during three surface faulting events that occurred at 31.8 ±2.8 ka, 28.5 ±3.7 ka and 3.0 ±0.3 ka B.P. The Khari river section is the most complete and the most well exposed section along the entire length of the KHF zone. The section was studied in detail to deduce the surface faulting parameters. The lateral extension of the surface faulting was determined using field evidences, GPR studies and microscopic studies using SEM. A slip history diagram to quantify the slip rate, is constructed by using the displacement values of 3.5m, 2.2m and 2.3m measured in the Khari river section. The slip rate thus calculated belonging to the three surface faulting events is 0.66mm/yr and 0.09mm/yr for the two seismic cycles formed from the three above-mentioned surface faulting events. The GPR survey carried out along the KHF zone to precisely locate the trace of KHF in the shallow sub-surface near Bharasar, Tapkeshwari, Bhujodi and Ler. At these locations, the GPR results confirmed the propagation of faulting from the Mesozoic rocks in to the overlying Quaternary sediments found on the surface.

The length of Late Quaternary surface faulting along the KHF is ~ 21 km as derived from the multiple evidences of surface deformation/faulting provided by field, GPR and microscopic studies. Based on fault parameters deduced like length of surface rupture, displacement and slip rate, the estimated magnitude of Late Quaternary surface faulting events and thus, the seismogenic potential of the KHF, calculated using empirical equations yielded M_w values consistently in a narrow range from 6.6 to 7.1. The field and GPR based study of the Gunawari and Gangeshwar river basins located in Katrol Hill Range shows that drainage reorganization occurred during the last ~30 ka B.P. in response to tectonic titling induced by surface faulting along the range bounding Katrol Hill Fault (KHF). The present study demonstrates that the KHF has produced high magnitude seismic events during the past ~ 30 ka B.P., and is, therefore, a potential seismic source capable of generating surface rupture hazard in the Kachchh Basin. As Kachchh basin is an intra-plate seismic zone source, long recurrence intervals between earthquakes, is not unusual, which forms an important input for evaluation of seismic hazard. A combination of approach that incorporates both the probabilistic and deterministic methods of seismic hazard assessment and also integrates the results contributed by various geological and geomorphic methods, including the present study, is suggested.

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