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

Synopsis
of the
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SYNOPSIS

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 (Mw 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 (Mw) 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.

REGIONAL GEOLOGY

The Kachchh rift was formed during early Jurassic as a consequence of the breakup of the western continental margin of India. Later part of the evolutionary history of the basin is linked to the northward drift of the Indian plate during which Mesozoic rift sediments were deposited and its subsequent collision with the Eurasian plate which led to the inversion of the basin under compression. The rift phase sediments deposited during the Mesozoic comprise the Jhurio, Jhumara, Jhuran and Bhuj formations. Inversion of the basin occurred due to onset of compressive stress induced by the collision of the Indian plate in the far north in early Cenozoic. This resulted in uplift of various crustal blocks due to uplifting movements along uplift bounding faults viz., the Katrol Hill Fault (KHF), Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and Island Belt Fault (IBF). In general, all aforementioned faults are roughly E-W trending and show vertical to steeply dipping fault planes.The present fault-controlled geomorphic configuration of Kachchh is attributed to inversion in the Late Cretaceous. In general, the post-rift geological evolution of the basin is marked byperiodic reactivation of various E–W trending intrabasinalfaults, which are also responsible for recurrent seismicactivity in the region. The first order topography and a longhistory of devastating earthquakes in recent past indicatecontinuous rejuvenation of the region.

OBJECTIVES

The present study was carried out to achieve the following objectives.

- Estimate the seismogenic potential of Katrol Hill Fault (KHF) based on geological datasets on neotectonics and active faulting
- Reconstruct seismic hazard scenario based on estimation of maximum possible earthquake along the KHF

APPROACH AND METHODOLOGY

1. Identification and mapping of various tectonic and geomorphic landforms, active faults based on satellite data, drainage patterns and preparation of base maps by satellite imagery interpretation.
2. Detailed geological and geomorphic mapping of Late Quaternary tectonic landforms and examining outcrops of Quaternary sediments lying precisely over the KHF.
3. Field mapping was supplemented by shallow sub-surface geophysical studies using GPR and Quaternary sediment sampling for microscopic studies including petrography and SEM.
4. GPR data processing and sample preparation in laboratory for analyses using optical microscope and high- resolution SEM.

5. Estimation of the surface rupture length, displacement and slip-rate of surface faulting events along KHF by integrating field evidences along with shallow subsurface GPR data and microscopic data obtained from optical microscopy and SEM.
6. The three estimated parameters of Late Quaternary surface faulting such as surface rupture length, displacement and slip rates were used to estimate the magnitude (Mw) of paleo-earthquakes by using different empirical equations.
7. Calculation of morphometric parametersand χ (chi) analysis to decipher the process of drainage reorganization in Gunawari and Gangeshwar river basins.
8. The data generated in the field as well as from multidisciplinary studies in the laboratory were synthesised and critically evaluated to delineate the implications of surface rupture hazard in Kachchh basin.

STRUCTURAL ATTRIBUTES OF KATROL HILL FAULT (KHF)

The E-W trending KHF has been mapped as a south dipping high angle reverse fault that confines the rugged hilly terrain of the KHR in the south and the northward gently sloping (~2°-5°) rocky plain developed over the Bhuj Formation to its north. It shows gentle dips of ~45°-50° in its western parts while steeper dipping plane is observed in the central and eastern parts. In general, the KHR is a large tilt block which comprises of domal structures along the fault line as evidenced by the consistent southward dips of the Mesozoic (Jumara and Jhuran) Formations. The elevation of KHR is highest at its northernmost part and decreasing southward which is in conformity with the tilt block structure. The hilly topography in this part is found over the E-W trending chain of domes all along the KHF. In addition to the rugged topography of the KHR, the range shows several E-W trending cuesta scarps formed over compact south dipping Mesozoic rocks. Consequently, deep E-W trending strike valleys have been formed that are occupied by streams.

Various geomorphic features such as gorges along Khari river and Gunawari river, terraces, fluvial hanging valley, defeated younger order drainages, pressure ridge, E-W trending line of north facing range front scarps, E-W trending back-valleys and sharp division of drainage into north flowing and south flowing rivers indicate a neotectonically influenced landscape.

QUATERNARY SEDIMENT COVER

At many places along its length, the KHF is buried under thin and patchy cover of Late Quaternary sediments. The sediments consist of colluvium, aeolian and fluvial (reworked) miliolites, sandy alluvium and scarp derived colluvium. Miliolite is the most abundant Quaternary deposit in the otherwise dominantly rocky terrain in Kachchh. 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.

LATE QUATERNARY SURFACE FAULTING -FIELD EVIDENCE

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 along the Khari river, which 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).

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.

SURFACE FAULTING PARAMETERS

Surface faulting events: 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).

Displacement and slip rate: 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 0.09mm/yr were associated with the three events of surface faulting which was calculated using the slip history diagram.

Length of surface faulting: Length of surface rupture is an important input parameter for determining the magnitude of paleo-events using empirical relationships. 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.

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 deformationto 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 asplane 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 depositsare 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.

The 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 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 onlyfluvial 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.

CALCULATION OF MAGNITUDE (Mw) OF SURFACE FAULTING EVENTS

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. 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. Since the evidence of surface faulting described above are all from miliolite deposits, it is obvious that the surface faulting had occurred in post-miliolite time and are related to the three surface faulting events along the KHF.

Based on the 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. Slemmons (1982) assumed that a fraction of total fault length will rupture during an earthquake and devised a relationship between the rupture length and magnitude for a reverse fault which yielded value of Ms as 6.9. The surface wave magnitude (Ms) was converted to moment magnitude (Mw) as the latter is a widely accepted parameter for earthquake magnitude. This was performed using the Ms to Mw earthquake magnitude empirical conversion.

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

Empirical relationship developed from a worldwide database of source parameters such as fault slip type, Ms, seismic moment, surface and subsurface rupture length, rupture width, rupture area and maximum and average displacement for 421 historical earthquakes, out of which 244 earthquakes with the most accurate parameters was also used in the present study. This has yielded moment magnitude (Mw) of 6.6 using the fault surface rupture length value of 21 kms.

Based on the displacement

The values of displacement and slip-rate of the three events of surface faulting used were obtained from the Khari river section. Using this information and stratigraphic displacement caused by the faulting events, the magnitude of surface faulting was calculated using a empirical relation. 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 (Mw) using the Ms to Mw earthquake magnitude conversion Using this conversion and substituting the Ms values of earthquake magnitudes obtained, the moment magnitude Mw 7.1 $\pm$0.45, 7.0 $\pm$0.44 and 7.0 $\pm$0.44 was obtained for the three surface faulting events along the KHF. Another empirical relationship yielded Mw values of 7.08, 6.9 and 6.9 for events 1 (oldest), 2 and 3 (youngest) respectively.

Based on the length of surface rupture and slip rate

This empirical relationship available is developed from 43 earthquake events for which Mw, surface rupture length (L) and fault slip rate (S) estimates existed and yields moment magnitude (Mw) as a function of fault rupture length (L) and fault slip rate (S). This is found to yield more accurate predictions for future earthquake magnitudes estimation as compared to the regressions based solely on fault rupture length (L). Substituting the values of surface rupture length (L) as 21 km and slip rate (S) for individual events of Quaternary faulting yielded the value- for the PE (Event 2) which took place in early Holocene showing the slip rate of 0.66 mm/year and for the youngest MRE (Event 3) which took place in late Holocene with a slip rate of 0.09 mm/year, provides Mw values of 6.6 $\pm$0.21 and 6.8 $\pm$0.25, respectively.

The Mw values obtained from different equations as mentioned above, are remarkably consistent. The Mw 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.

LATE QUATERNARY 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 asymmetricaldomes 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 SURFACE FAULTING 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 year, 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, Sahel Algiers 1989 and the Mascara 1994, reinforce the idea that surface faulting in the KHF is a potential source of future large earthquakes.The data presented will contribute to a better understanding of the seismic hazard in the areas around KHF. Furthermore, the multidisciplinary procedures may be needed to decide the measures needed to reduce the effects of surface rupture hazard.

INFERENCES

The present study has led to following inferences.

- KHF is a steeply dipping reverse fault which becomes vertical at depth.
- The KHF scarps have retreated towards the south from the actual fault line and the amount of retreat varies in every segment.
- Field mapping, GPR studies and microscopic evidence (petrographic and SEM data) have revealed that at least 21 km length of the KHF was affected by three surface rupturing events at 31.8 ka, 28.5 ka and 3 ka B.P.
- Based on fault parameters deduced like length of surface rupture, displacement and slip rate, the estimated magnitude of surface faulting events using empirical equations have yielded Mw values consistently in a narrow range from 7.1 to 6.6.
- The present study demonstrates that the KHF has produced high magnitude seismic events during the past ~30 ka B.P., and is, therefore, a credible seismic source capable of generating surface rupture hazard in the Kachchh basin.
- Previous surface faulting events suggest a much long recurrence interval for the KHF compared to other seismically active faults in the Kachchh basin.
- Geomorphic features like wind gap, buried paleo-valley, aeolian and fluvially reworked Late Quaternary miliolite deposits, along with anomalous channel reaches along the Gunawari River such as along strike straight channel segments and the unusual “V”- and “S”-shaped bends with knickpoints suggest drainage rearrangement of drainage lines occurred during the last ~30 ka BP in response to tectonic titling induced by surface faulting along the range bounding KHF.