CHAPTER – 11

DISCUSSION

Katrol Hill Fault (KHF) is an intra-basinal range bounding fault, which divides the Kachchh mainland into two divisions - the rugged topography in the south comprising the Katrol Hill Range (KHR) and the low-relief rocky plain to the north is dominated by Late Cretaceous fluvio-deltaic Bhuj Formation (Biswas, 1993). The E-W trending KHF has been mapped as a south dipping high angle reverse fault, which 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, forming a flexure zone along the Faultline (Maurya et al., 2003a, b). 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 and Gunawari rivers, 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 (Patidar et al., 2007; 2008).

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 (Patidar, 2010). The bouldery colluvium deposits found overlying the Mesozoic rocks at the basement are the 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 (Patidar et al., 2007; 2008). The overlying aeolian and valley-fill or fluvially reworked miliolites are the most commonly encountered varieties of miliolites. The aeolian miliolites were deposited as obstacle dunes in front of and along the foot-hill region of the north facing scarps, burying the KHF partially and also in valleys and depressions within the hilly terrain of KHR. Some parts of these deposits have been reworked by stream action forming valley-fill or fluvially reworked miliolites, which are readily distinguished in the field by horizontal stratification and presence of pebbles and boulders of Mesozoic rocks.

LATE QUATERNARY SURFACE FAULTING

Evidence from field studies

The Quaternary deposits always play an important role in deciphering the neo-tectonic activity of the region and in delineating the seismogenic potential of seismically active faults. These deposits occupy the Ranns, the alluvial Banni plains, in the Northern Hill Range at the base of fault scarps and cliff sections of various streams and along the coastal alluvial plains towards the south of Mainland Kachchh (Thakkar et al., 1999; Maurya et al., 2003a). Out of all different kinds of Quaternary deposits obtained in the Kachchh basin such as the clay deposits, alluvial plains, colluvial fans, pedogenized fluvial sand-silt and gravels, assorted colluvial deposits and miliolites, the miliolite deposits have been delineated as an important stratigraphic and chronographic horizon (Biswas, 1971; Thakkar et al., 1999). Strong, north-westerly wind currents are noted as the main cause of deposition of miliolites from the coastal region to far-off inland areas in Kachchh (Biswas, 1971). The aeolian miliolites were mostly deposited at the foot hill regions of the scarps that posed as an obstruction to the wind currents; while, the downward passage and redeposition of the aeolian deposits in the valleys and other depressions due to the effect of gravity and seismicity formed the valley-fill or fluvially reworked miliolites (Biswas, 1971).

The KHR occupying the southern area of the Mainland Kachchh, is characterized by the presence of different sediments belonging to Late Quaternary such as boulder colluvium at the base, overlain successively by aeolian miliolite, valley-fill/ fluvial miliolite (reworked), sandy alluvium and scarp derived colluvium. A composite litholog in Figure 4.1 depicts a generalized litho-stratigraphic succession of these deposits in the KHR. The aeolian and fluvial varieties of miliolite deposits are the most commonly found varieties along the KHF zone. The occurrences of these miliolite deposits in foot-hill regions and in front of the scarps and in the valley depressions can be clearly appreciated through the topographic profiles (Figure 4.2b) constructed across the KHR and KHF at locations specified in Figure 4.2a.

A succession of Quaternary sediments overlying the Mesozoic rocks on the left bank of Khari river cliff section displays offsetting among the Quaternary sediment layers (Figure 5.3) due to faulting along KHF in the Mesozoic rocks that propagated upwards into the overlying Quaternary layers also. The Quaternary units found in the Khari river section comprise of: unit-1 Bouldery colluvium, unit-2 Gravelly sand, unit-3 Stratified miliolitic sand and unit-4 Scarp-derived colluvium, the bases of these units are erosional. The above-mentioned units are observed to be displaced due to the occurrence of three Late Quaternary surface faulting events (Figure 5.3) at 31.8 ±2.8 ka (Event 1), 28.5 ±3.7 ka (Event 2) and 3.0 ±0.3 ka B.P. (Event 3) (Patidar et al., 2008; Kundu et al., 2010). At this location, the splaying nature of the KHF can be noticed as the fault plane (F1 and F2) enters the Quaternary sediments from the underlying Mesozoic rocks, displaying gentler dips in the former.

The slip history diagram (Figure 5.5) is constructed by plotting the displacement along the fault measured during the field survey against time. This diagram depicts temporal changes in displacement along KHF (Tiwari et al., 2021). 3.5m, 2.2m and 2.3m of displacement along the fault was measured during field studies, which correspond to 31.8 ±2.8 ka (Oldest earthquake – OE), 28.5 ±3.7 ka (penultimate earthquake – PE) and 3.0 ±0.3 ka B.P. (most recent earthquake – MRE) respectively (Table 5.1). The slip history diagram yields the “paleo-seismic slip rate” of 0.66mm/yr for the closed seismic cycle of 3.3 ka formed between the oldest earthquake (OE) and penultimate earthquake (PE); while, the period of 25.5 ka between the penultimate earthquake (PE) and most recent earthquake (MRE) records the slip rate of 0.09mm/yr. As the seismic event preceding the oldest earthquake (OE) event and that succeeding the most recent earthquake (MRE) is not known and not yet occurred respectively, they are considered as open seismic cycles and so not included in the calculation of slip rates. The slip rate calculated by considering the closed seismic cycles is the actual paleo-seismic slip rate or true slip rate as there are no changes or alterations in the length of closed seismic cycles. Regardless of the above situation, if the slip rate is estimated by incorporating the length of open seismic cycles, an “apparent slip rate” of 0.25mm/yr is obtained.

The sparsely distributed nature of the Quaternary deposits along the KHF and surrounding areas has exposed the fault plane of KHF in the Mesozoic rocks. Towards the SE of Mankuva (west), it can be observed that the construction of TV tower has taken place in the KHF zone (Figure 5.1a). At some locations like east of Shiv paras, and along Ashapura volclay road near Ler village (east) with the dip amounts of 69° and 83° due S respectively with the presence of scarp in the background towards the south (Figure 5.1b, c).

An outcrop displaying deformation in Late Quaternary deposits as well as vertically dipping aeolian miliolite beds are found along the trace of KHF, located towards south of Bharasar and south of Bhujodi village respectively. The deformed Late Quaternary deposits overlying the Mesozoic fault plane of KHF found towards the south of Bharasar is located on eastern bank of a NE flowing lower order tributary of Khari river, situated very near (~3 km) to the Khari river cliff section. In addition to this, the miliolite outcrop found south of Bhujodi (Figure 5.6) showed almost vertically dipping plane consisting of foresets of thinly-laminated aeolian origin cross-bedded miliolite. These foresets display gentler dips as one moves away from this site towards the north.

Other than the three locations mentioned above, i.e., Khari river section, south of Bharasar and Bhujodi areas (marked as QD in Figure 4.2a and 5.2), the area around KHF is characterized by the lack or absence of outcrops showing evidence of any kind of deformation in the Late Quaternary deposits (Tiwari et al., 2021). Therefore, in order to perceive the shallow sub-surface nature of KHF and demonstrate the lateral continuity of the trace of KHF, GPR surveys were carried out after precisely mapping the area around KHF geomorphologically and neotectonically.

Evidence from GPR surveys

GPR survey was performed at four different locations across the KHF plane from west to east namely, Bharasar, Tapkeshwari, Bhujodi and Ler to precisely locate the shallow sub-surface trace of the KHF and to observe whether the faulting along KHF has affected and displaced the unconsolidated to semi-consolidated Quaternary deposits that overlie the Mesozoic rocks. The vertical movement along the fault plane is detected by the reflectors in the GPR profile, which tend to offset or deflect across the plane of faulting and therefore, indicate the presence of the fault plane. In the present study, the GPR profiles recorded across the KHF (N-S transect) at the four locations show the presence of KHF in the Mesozoic rocks, which propagates into the overlying Quaternary sediments, as indicated by sudden change in the amplitude and dip of reflectors across the fault plane. The Quaternary – Mesozoic interface is marked by changes in the reflector pattern and amplitude. In the present study, precise location of KHF has been identified at four different locations, such as Bharasar, Tapkeshwari, Bhujodi and Ler, which also point towards the variable thickness of Quaternary deposits in the shallow sub-surface along the KHF zone, in addition to the field evidences of Late Quaternary sediments showing variable thickness among different outcrops (Figures 4.3 and 4.4). As the main objective of the GPR survey was to precisely locate the trace of E-W trending KHF in the Late Quaternary deposits occupying the shallow sub-surface, all the profiles are oriented in N-S direction to properly appreciate the presence of fault plane and associated deformation. Also, a 200 MHz frequency monostatic antenna in continuous mode has proved to be adequate enough to acquire all the profiles across KHF, as the requirement of depth in the present study to observe Late Quaternary sub-surface deformation was not very high.

At Bharasar, the GPR profile (marked as T4 in Figure 5.2) recorded along a north-flowing tributary of Khari river shows Quaternary-Mesozoic interface at ~ 60-70 ns (TWT), which distinguishes the scattered low amplitude, discontinuous reflections of Mesozoic rocks at the lower section and high amplitude continuous reflections from the lithified Quaternary miliolite sediments continuing up to a depth of ~ 3-4 m from the surface (Figure 6.5). A southward dipping KHF fault plane can be clearly noticed along the 15-25 m of distance, indicated by offset and deformed reflectors. Different features such as younger onlapping sediment wedges, erosional channel scour, erosional scour and fill sediments and valley-fill miliolites can be delineated based on specific pattern of reflectors and variation of amplitude among the reflectors.

The other site was located on Bhuj-Tapkeshwari road (marked as T5 in Figure 5.2) where a 45 m long GPR profile was acquired, and the Late Quaternary sediments are seen occupying the upper ~3 m (50-75 ns) of the profile (Figure 6.6) starting from the surface and is characterized by the presence of features such as Quaternary colluvio-fluvial wedges, younger channel scour and fills, erosional scour and traces of valley-fill miliolite as suggested by difference in pattern and amplitude of reflectors. The Quaternary-Mesozoic interface observed at ~3m of depth is marked based on the contrast between the reflector geometry and amplitude; while the fault plane is delineated by the presence of abruptly truncating and deformed reflectors.

GPR survey was also performed in the Bhujodi area (marked as T3 in Figure 5.2), which already provided the field evidence of deformation in the form of vertically dipping aeolian miliolite beds due to faulting (Figure 6.4). As observed on the surface, the steeply dipping (~ 85°) almost vertical nature of deformation of aeolian miliolite beds can be undoubtedly appreciated in the subsurface as well. Here, the Quaternary deposits are noticed up to ~ 5.5 m of depth, which display abruptly steepened and almost vertically deformed miliolite beds (~20-25 m distance), marking the KHF plane along the trace of truncation (~24 m distance) of miliolite beds. They also show erosional channel cut features, which are successively filled by the younger sediments. The north dipping reflectors after crossing the KHF plane in the GPR profile, attain opposite dip towards south. The Quaternary-Mesozoic interface can be marked by the presence of an unconformity between the two different layers of rocks.

A 90 m GPR profile marked as T6 in Figure 5.2 was recorded across the KHF trace found in the Ler village. At this site (Figure 6.7), the Quaternary sediments are present up to ~3 m of depth, which indicates the Quaternary-Mesozoic interface through distinct variations in the reflection pattern. The sudden offsetting and truncation of reflectors at ~ 55 m distance characterizes the presence of a gently dipping KHF plane in the Mesozoics as well as Quaternary deposits.

Microscopic evidence

For the locations along the trace of KHF, which were covered by the Late Quaternary deposits, the processed GPR data provided evidence of its deformation and conformed the propagation of faulting into the Quaternary sediment subsurface layers pointing towards post-miliolite surface faulting along KHF at multiple locations (Tiwari et al., 2021), which cannot be observed during the field studies.

With the help of the data provided by the GPR studies about the precise location of the KHF plane, samples from these Late Quaternary deposits found overlying exactly over the KHF trace were collected to detect the microscopic evidences of deformation due to surface faulting.

<u>Thin-section studies of fluvial and aeolian miliolite samples</u>

The thin-section analysis of fluvial and aeolian miliolite samples (Figure 4.6) collected from the KHR reveal that they mainly consist of mineral grains of quartz, pyroxene microcline and (augite – very rare) and, bioclasts of bryozoans, foraminifera, algae, shell fragments and pellets, which are held together by calcareous cement. As the constituents and cementing material of both the varieties of miliolites display similarities, variation can be seen in them with respect to the roundness of the grains, grain sorting and the type of contact between the grains. More rounded to sub-rounded and well sorted grains are found in the aeolian miliolite sample, while the grains belonging to fluvial miliolite sample are sub-rounded to sub-angular and display poor sorting among the grains. Point contact relationship is observed between the grains of both aeolian and fluvial miliolite samples, but in case of aeolian sample, the very few grains tough each other’s boundaries. This property demonstrates highly porous and friable nature of the rock with very less compaction after its deposition. On the contrary, the fluvial miliolite sample shows point contact with every other grain touching other grain boundaries points towards a little more compact nature in comparison to aeolian miliolites, which may be responsible for sheet like appearance of the fluvial miliolite outcrops in the field. The reworked nature of the fluvial miliolite samples is shown by the higher amount of broken shell fragments in them.

Thin-section studies of the samples collected from the KHF fault trace

The thin section of the samples collected from both types of miliolite deposits located along the KHF zone (sites S3 to S8 marked in Figure 4.2a) showed the presence of the faulting-related microfeatures. The thin-section of aeolian and fluvially reworked miliolites exhibited development of microcracks along the grain boundaries of detrital mineral grains and prominent breakage and fracturing of peloid bioclasts (Figure 7.1) without significant distortion of the original grain shape. The thin-section of fluvially reworked miliolites and aeolian miliolites demonstrated shape-preferred orientation among the elongated allochems and detrital mineral grains (Figure 7.1 and 7.2). The formation of macro-sparite by recrystallization of calcitic cement and detrital quartz grains is also observed in thin-sections of miliolites of both the origins (Figure 7.1 and 7.2). Here, calcitic microfibres are also observed on the grain boundaries of recrystallized peloid bioclasts (Figure 7.1 and 7.2). Rare occurrence of polycrystallinity of quartz grains displaying undulose extinction (Figure 7.1 and 7.2) is observed in grains >300-350μm. Conolly (1965) suggested that close proximity of faulting frequently induces undulatory extinction in quartz grains. The observation of orientation among particles have been made within the poorly lithified sediments by Loveless et al. (2011). The characteristics, such as microfractures/microcracking, shape and crystallographic orientation relation of grains and recrystallization, provide important information about the deformation and stress histories in natural shear zones from different tectonic regimes (Wilson et al., 2003; Trepmann et al., 2017). Abundant evidences of grain breakage and shape preferred orientation of grains was also observed in the thin-sections of fault zone rocks of Alder Creek on the North Coast South segment of San Andreas Fault (Cashman et al., 2007). Thus, the breakage, slight orientation, recrystallization and undulose extinction of grains observed in the present study can be attributed to the seismic activity along the KHF after the deposition of miliolite deposits. On this basis, it is suggested that the miliolite deposits must have been affected by recent tectonic activity, which indicates post-miliolite reactivation of the KHF.

SEM studies

The quartz grains separated from the fluvial miliolite samples (Figure 4.7 and 4.8) were mostly sub-rounded and sub-angular to angular and showed a variety of microtextures resulting from breakage of grains such as uneven grain boundaries, unoriented fracturing, radial fractures, parallel fractures, step like fractures, straight and curved fractures, conchoidal fractures, fresh fractured grain surface and large breakage blocks. These breakage microtextures are related to conchoidal fractures (Vos et al., 2014) and result due to the intersection of conchoidal fracture plane with the cleavage plane of quartz crystal.

Solution action is indicated by smoothened grain surfaces and edges by filling in the depressions and dissolving the protruding areas on the surface. The solution activity also exposes the underlying cleavage plates of quartz grain. Chemical action also leads to the development of chemically altered and etched surface displaying pitted and grooved surface, irregular pits and depressions, solution pits (Higgs, 1979). Microtextures such as crescentic gouges and randomly oriented V-shaped percussion marks are produced due to severe grain-to-grain collisions and collisions between the grains where plates along cleavage surfaces are broken at numerous places respectively (Campbell, 1963; Margolis and Krinsley, 1974). Different stages of silica precipitation such as silica globules, silica flowers and silica pellicle can be observed on the grain surfaces in Figure 4.8, which can be attributed to diagenetic processes.

The quartz grains belonging to aeolian miliolite samples (Figure 4.9) were mostly rounded to sub-rounded and frequently consisted of bulbous edges. Abraded edges of the grain, weathered and rough surface, silica precipitation in the small grooves, etched surface and irregular solution pits are created due to the chemical action on the grain surface (Higgs, 1979). Microtextures formed due to solution action are smoothened irregular depressions on the grain surface, smoothened remnants of conchoidal fractures. Fracture patterns like patches of fresh fracture surfaces, linear fractures, small and large conchoidal fractures, upturned plates, broken and curved groove surfaces, straight or parallel fractures, radial fracture pattern, linear and parallel ridges and v-shaped and crescentic percussion marks result because of grain collision during the transportation of these sediments by high velocity winds. The presence of adhering particles has been noticed as a common microtexture of aeolian quartz grains.

Results from the SEM analyses show that broad similarity exists between the range of fluvial microtextures of miliolite samples collected from the sites both along (Figure 4.2a, marked as S1 to S9) and away (Figure 4.2a, marked as S1* to S6*) from the KHF zone. The grain surfaces essentially show irregular, parallel to sub-parallel, step-like fractures and conchoidal breakage pattern typical to quartz grains; together with the mechanical microtextures (Figure 4.7 and 4.8) produced on the grain surface due to fluvial transport (Vos et al., 2014). Chemically induced microtextures such as solution pits were also found, which resulted from the enhanced chemical action on the rock (Figure 4.7). The aeolian origin quartz grains sampled from the location along the KHF zone dominantly showed features typical of aeolian transport processes (Figure 4.9). The patchy occurrences of silica precipitation observed on the grains of both aeolian and fluvial miliolites indicates weak diagenesis of the rock (Krinsley and Doornkamp, 1973).

In addition to the microtextures such as striation and exfoliation (Figure 7.4, 7.8), fresh fractured surfaces, rolled (Figure 7.6a to f) and euhedral quartz grains (Figure 7.6g, h and i) and adhering particles (Figure 7.5), the intensity of grain fracturing/breakages (Figure 4.7, 4.9, 7.3, 7.7) was observed to be high on the samples of both fluvial and aeolian origin collected from along the KHF trace from Bharasar to Ler (samples S3 to S8, marked in Figure 4.2a). The striations can closely be associated with those noticed on the surface of quartz grains from fault gouge samples derived from the Atotsugawa fault (Kanaori, 1983) and central Japan (Niwa et al., 2016). Mahaney (2002) also considered striations as a characteristic property of grains from fault environments.

Mahaney and Sjoberg (1993) attributed the occurrence of exfoliation marks on quartz grains to neotectonic processes. The exfoliation feature on grain surface mostly develops when there is a sudden release in the confining pressure, which can possibly occur due to faulting (Mahaney, 2002). Along with the presence of striations, the grains are observed to be heavily pitted and fractured. The rolled and crystallographically realigned quartz grains as observed in the present study are also common in massive large-scale faults such as the San Andreas (Mahaney, 2002). Intense fracturing of the quartz grains has exposed the cleavage planes.

Kanaori et al. (1980a, 1985) and Kanaori (1983) did a detailed study of the surface textures of quartz fragments in fault gouges. The occurrence of fresh (smooth) fracture surfaces and intensively broken surfaces is attributed to fault activity as the samples were all derived from the fault zones (Kanaori, 1983; Kanaori et al., 1985). Excessively fractured grains were also recovered from the gouge zone of the Boconó Fault (Venezuela), which resulted due to the movement along faults (Mahaney, 2002). Sawtooth fractures are also reported to be produced from the neotectonic release along the faults (Mahaney, 2002). The phenomenon of developing microcracks along the grain boundaries was also determined to provide a criterion to characterize rock masses around a fault as it was observed in the samples of the Atotsugawa fault (Kanaori et al., 1991).

Barcilon and MacAyeal (1993) considered that the sudden release of stress along a short displacement fault produced crushing and abrasion features, and this increase in stress results in enormous pressure generated along grain-to-grain boundaries, which leads to the development of intensely fractured and cratered surfaces. Lastly, the grains are examined to have adhering particles (Figures 7.5 and 7.8) of medium to coarse silt to fine sand that appear to be a diagnostic of faulting leading to grain fractures (Mahaney et al., 2004). This similarity between the microtextures of quartz grains of two different environments (fluvial and aeolian) points to a common deformational mechanism in action. It is interpreted that neotectonic processes along the KHF are responsible for the development of the aforesaid microtextures.

The fact that there is a clear spatial relationship of the microtextures, such as striation, exfoliation, excessive breakage, adhering particles and rolled quartz grains with distance from the fault zone suggests that these microtextures are likely to be fault related. However, in order to rule out the formation of the microtextures by weathering processes, samples of quartz grains located away from the fault zone and away from the surface rupture trace (samples S1* to S6* and S1, S2, S9 marked in Figure 4.2a) were also examined as shown in Figures 7.10 and 7.11. The SEM data shown in Figures 7.3 to 7.9 clearly demonstrates the role of tectonic processes on the samples collected from along the fault zone. Also, it is to be noted that the erodibility of miliolite deposits found along and away from the KHF zone is equal. The quartz grains of the samples from the sites located away from fault plane (Figures 7.10) and away from the trace of surface rupture (Figure 7.11) showed most of the charateristics of fluvial and aeolian transport process. The quartz cleavage plates were also not seen in the above samples, which indicates that the grains are intact and have not undergone much breakage. And thus, it can be postulated that weathering is not the cause of the occurrence of the aforesaid microtextures observed in the quartz grains along the KHF zone.

The microtextures such as extensively broken and fractured grains, striation, exfoliation, rolled and euhedral quartz grains observed at the sites along the KHF zone indicate seismically induced activity as a contributor to the development of Quaternary sediment microtextures. Moreover, the similarities of microtextures in all the samples analysed in the present study with various other fault zones in the world seem to support the generation of the above mentioned microfeatures due to recent tectonic activity along the KHF. Taking into account the micromorphological (thin-section) and microtextural (SEM) observations in the study area along the KHF, it can be confirmed that the deformation due to faulting during the Quaternary period has reached up to the surface in the segment of the KHF from Bharasar to Ler, which is estimated to be ~ 21 km.

GEOMORPHIC EFFECT OF SURFACE FAULTING ALONG KHF – DRAINAGE REORGANIZATION

Drainage realignment is known to occur in three ways – capture, diversion, beheading and reversal (Bishop, 1995). River capture involves the progressive encroachment of one catchment boundary into the adjoining catchment through headward erosion while river diversion includes redirection of drainage into an adjacent catchment by a range of mechanisms of divide breaching like channel migration, tectonics (including tilting, doming, etc.) or catastrophic 'avulsion' by high-magnitude flows (Bishop, 1986). The term beheading, covers appropriation (or abstraction) of a river's catchment area to an adjacent river (Bishop, 1995). 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. (Maurya et al., 2021). 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 (Figure 9.9c). The formation of the anomalous 'V'-shaped bend (Figure 9.3c) is a consequence of drainage response to uplift superimposed over local factors. Abandonment of buried paleo-valley occurred through river diversion as the river could not continue to flow in an uptilted direction and was forced to carve an eastward straight channel along Tributary 2 reversing its flow direction and extending its course along the strike of beds. The westward progressing headward erosion of paleo-Gunawari joined with the eastward directed new channel producing the 'S'-shaped bend (Figure 9.3f, 9.3g) forming the elbow of capture (Figure 9.9c). Erosion induced by tectonic uplift dominated throughout the process of drainage rearrangement as evidenced by the deeply incised channel in miliolite deposits (Figure 9.3b), falls and knickpoints (Figure 9.3d, 9.3f and 9.3g).

River diversion occurs by top-down processes (Bishop, 1995) and involves redirection of an upper drainage into an adjacent river system lying at lower elevation. The mechanism of river diversion is much less understood than river capture. In general, river diversion is a less energy- consuming way of modifying a river network, because it only implies the localized removal of a watershed and does not require significant modification of the network of flow lines (Brocard et al., 2011). However, river diversions have been widely reported, but the exact processes involved in the diversions are generally poorly documented, because the diagnostic features of such processes generally quickly disappear after a diversion, which means that proving diversion is difficult (Bishop, 1995; Brocard et al., 2011; Authemayou et al., 2018). In the case of the present study area, the role of river diversion and the occurrence of top-down process is found to be prominent during the drainage realignment in Gunawari river basin (Maurya et al., 2021). The top ends of the 'V'-shaped bend provide evidence of diversion of channel away from the miliolite filled paleo-course at two closely spaced locations. At both places, the swing of the channel is in conformity with southerly directed tectonic tilt that points to the role of top-down process.

The 'V'-shaped bend consists of eastward and westward arms that join forming an extremely acute bend (Figure 9.3c). In the western arm, the river flows towards SSE, which conforms with the southerly tectonically controlled regional slope. It is therefore inferred that this arm of the bend represents top-down process that forced the river away from the sediment-filled paleo-valley and to turn to the SSE in the direction of tectonic tilting. However, in the eastern arm of the bend, the river flows in the anti-dip direction i.e., in NNE direction. A small incising tributary arising from the Marutonk dungar hill in the south and flowing in the NNE direction joins the Gunawari river from the south at the apex of the 'V'-shaped bend (Figure 9.9b). The trend of the tributary (Tributary 1) is the same as the eastern arm of the bend. The channel of the Gunawari river flowed towards SSE in the western arm of the bend joined up with the tributary (Tributary 1) and followed its channel direction forming the 'V'-shaped bend.

Significantly, the river-bed elevation of the Gunawari river in the eastern arm of the bend drops by ~20 m within a distance of ~100 m. The drop is seen in the form of a series of falls in the bedrock (Figure 9.3d). The formation of the fall zone in the eastern arm of the bend is a response of the river to reach the zone of greater incision depth in softer miliolite rocks in the downstream. However, the up-dip flow direction of the channel in this arm indicates a role of tectonic uplift in the formation of the anomalous 'V'-shaped bend (Figure 9.9d). Bishop (1995) reported that the occurrence of knickpoint is an important feature that is associated with drainage realignment. The incision rapidly increases from ~7 m at the apex of the 'V'-shaped bend to ~35 m in this reach (Table 9.1). At the downstream end of this eastern arm of the bend, the miliolites show abrupt increase in thickness to ~40 m (Figure 9.3e), which is the part of the sediments that fill up the wind gap described earlier. It is interpreted that the miliolites at this location along with those in the buried paleo-valley mark the channel of the paleo-Gangeshwar river (Figure 9.9a), that was overwhelmed by wind deposited miliolite sediments (Figure 9.9b).

Between the ‘V’ and ‘S’-shaped bends, this channel reach was formed during drainage reorganization as the river turned sharply towards east abandoning its north oriented course through the wind gap and buried paleo-valley (Figure 9.3a). The river could not maintain its northward course due to relatively greater uplift of the floor of the north trending buried paleo-valley and wind gap as they lie in the uptilted direction. Due to the effect of southward tilting, the paleo-valley between the Ler and Gangeshwar domes that form the northernmost part of the KHR consequently underwent relatively greater amount of uplift. Thus, the paleo-valley and the wind gap also gained more elevation, which effectively disrupted the flow of the paleo-Gangeshwar river through the paleo-valley and wind gap. The river therefore carved out a straight eastward course through the Mesozoic rocks at the southern fringe of the Ler dome (Figure 9.9c). This is supported by the fact that presently, the floor of the wind gap occurs ~10 m above the river bed level at this bend (Figure 9.6b). The occurrence of miliolite for some distance towards the east beyond the ‘V’-shaped bend (Figure 9.9b) indicates a pre-existing small physiographic low. It is suggested that this low was occupied by Tributary 2 that joined the channel of the northward flowing paleo-Gangeshwar (Figure 9.9b). Due to abandonment of the paleo-course in the wind gap and paleo-valley, the river turned eastward along the Tributary 2 reversing its flow direction. Further extension of the E-W trending straight course up to the ‘S’-shaped bend occurred by top-down process. The channel was formed along the E-W trending beds of soft shale with the hard fossiliferous limestone bed lining its left bank (Figure 9.3f, 9.3h). It is interpreted that this E-W trending channel was produced by top-down process (indicated by TD in Figure 9.9c) of river diversion as the paleo-Gangeshwar river was forced to turn eastward causing reversal of Tributary 2 and flow along the strike of beds as its floor in the paleo-valley in the up-tilt direction was raised due to tectonic uplift.

Along strike river diversion towards east led to disconnection of the part of the channel in the north oriented paleo-valley and the wind gap with the headwaters resulting in beheading (indicated by B in Figure 9.9c). The beheaded stream corresponds to the present day Gangeshwar river whose source is located at the northern end of the wind gap and flows towards north along a narrow but deeply incised channel (indicated by B in Figure 9.9c). The narrow gorge-like channel of the Gangeshwar river has a comparatively greater depth of incision compared to the Gunawari river in its E-W trending channel in the back-valley. The increased incision by Gangeshwar river is attributed to an increased effect of southward tilting. Deep incision by the beheaded north flowing Gangeshwar river was primarily influenced by tectonic uplift. The depth of incision is greater as it is located closer to the scarps and the KHF in contrast to the Gunawari river, which flows in the strike parallel back-valley to the south (Figure 9.3a). Since the river flows through the northernmost margin of the fault bounded Katrol Hill Range, it suffered relatively more tectonic uplift due to south directed tectonic titling induced by surface faulting along the Katrol Hill Fault. Also, the incision occurred in the softer miliolite sediments and not in hard, compact Mesozoic rocks. The Gangeshwar river, therefore, could incise deep in spite of its reduced source area and consequent low stream power.

River capture is often described as an aggressive mechanism of drainage rearrangement (Bishop, 1995; Aslan et al., 2014; Willett et al., 2014; Lavé, 2015). It involves upstream directed rapid erosion by captor stream that is located at a lower level than the victim stream (Bishop, 1995). This is achieved by bottom-up process comprising upward propagation of erosion leading to wearing down of the interfluves completing the final capture of the stream at higher level. The bottom-up processes induced headward erosion (indicated by H in Figure 9.9c) was accomplished by the paleo-Gunawari river, which was a short stream located in the saddle zone at the eastern flank of the Ler dome prior to ~30 ka B.P. Being located in the saddle zone; it was certainly at a lower elevation compared to the paleo-Gangeshwar river. The ~10 m high cliff at the 'S'-shaped bend (capture point) exposing mostly south dipping soft shales (Figure 9.3f) gives a rough estimation of the higher elevation of the breached drainage divide. Tectonic tilting due to reactivation of KHF in the last ~30 ka caused the paleo-Gunawari to extend its course westward through active headward erosion (indicated by H in Figure 9.9c) along the strike of the beds at the southern flank of the Ler dome. This resulted in the formation of strike controlled straight, narrow and incised but shallow channel. The westward extending channel of the paleo-Gunawari river joins up with the channel of the paleo-Gangeshwar river of same orientation and that was progressing eastward through top-down processes (Maurya et al., 2021).

The two E-W trending straight channels advancing towards each other were not aligned in the same line. Due to this the joining up of the two channels and an anomalous 'S'-shaped bend (Figure 9.3f, 9.3g) formed from two right angle bends thus making up the channel set up of the present day Gunawari river (Figure 9.9c). The 'S'-shaped bend is therefore the capture point/elbow of capture formed during the process of drainage rearrangement in the area (Figure 9.9c). The anomalous 'S'-shaped bend is a consequence of mismatch in alignment of the two newly developing strike controlled channels in response to tectonic uplift, one was formed by the tendency of the paleo-Gangeshwar river to flow eastward by top-down process along the reversed channel of pre-existing Tributary 2, as its former course was disrupted due to uplift and the other was progressing westward along strike through headward erosion by the paleo-Gunawari river located in the saddle at the eastern region of Ler dome. The difference in elevation of the two channels is reflected by the two knickpoints at the right-angle bends forming a composite ‘S’-shaped bend. The cumulative elevation drop of the river bed in the ‘S’-shaped bend is ~5 m (Figure 9.3g).

Taking into account the evidences described in the foregoing discussion, it can be inferred that the deposition of miliolite deposits in the course of the paleo-Gangeshwar river channel blocked its path (Figure 9.9b, 9.9c) as indicated by the occurrence of aeolian miliolite deposits with intervening fluvial miliolite deposits in the wind gap and paleo-valley (Figures 6.2 and 6.3). Later, regional southward tilting due to the reactivation of KHF reversed the flow of the north flowing paleo-Gunawari river and initiated headward erosion westwards resulting in the stream capture at the elbow of capture (Maurya et al., 2021). In view of the previously documented three events of surface faulting along KHF (Patidar et al., 2008), which extends into the Gunawari basin, it can be concluded that coseismic tectonic activity along the KHF in the last ~30 ka B. P. resulted in uplift and tilting of the KHR, which caused river capture and drainage realignment (Figure 9.9c) in the Gunawari river basin.

CHARACTERISATION OF KHF AS A POTENTIAL SEISMOGENIC SOURCE

Estimation of the magnitude of paleo-events requires knowledge of faulting parameters like length of surface rupture, displacement, slip-rate and others (Wyss, 1979; Slemmons, 1982; Schwartz et al., 1984; Wells and Coppersmith, 1994; Anderson et al., 1996). As described above, the length, displacement and slip-rates related to the Late Quaternary surface faulting events along the KHF have been estimated. The largely erosional rocky topography and extremely patchy nature of Quaternary sediment cover over the KHF contributed to designing the approach and selection of methods to be used in the present study. The displacement and slip-rate were determined from the chronologically constrained Khari river section. Field, GPR and microscopic evidence of Quaternary deformation along KHF show that the trace of surface rupture is at least ~21 km long. The various parameters of Late Quaternary surface faulting delineated are shown in Table 5.1. The magnitude of the Late Quaternary surface faulting events is estimated following the empirical relationships of magnitude v/s various fault parameters (Table 8.1) developed by Slemmons (1982), Wells and Coppersmith (1994) and Anderson et al. (1996). The main purpose of using multiple methods and multiple parameters was to have a check on the consistency of the values of estimated magnitudes. Consistency of the values would mean that these could be used reliably for estimating the seismic hazard accurately along KHF.

For estimating the magnitude of Late Quaternary surface faulting events, multiple empirical relationships that use the length of surface rupture, displacement and slip rate developed by (Slemmons, 1982; Wells and Coppersmith, 1994; Anderson et al., 1996) were utilized. Incorporating the deduced length of surface rupture (~21 km) in Eq. (2) (Wells and Coppersmith, 1994), M_w 6.6 as the magnitude value of the causative event was obtained. Based on the length of surface rupture (Slemmons, 1982), the M_w value was obtained as 6.8 $\pm$0.44. Since the deduced length of surface rupture is the cumulative length of all three events, this value is taken as a general indicator of the magnitude responsible for the creation of a rupture of this length.

Based on maximum displacement, the derived M_w values are 7.08 (event 1), 6.94 (event 2) and 6.95 (event 3), which is the youngest event. Incorporating the displacement values (Slemmons, 1982), the M_w values as 7.1 $\pm$0.45 (event 1), 7 $\pm$0.44 (event 2) and 6.9 $\pm$0.44 (event 3) for the youngest event were obtained. Using the length of surface rupture together with a slip rate for calculating the magnitude of events (Anderson et al., 1996), M_w values of 6.6 $\pm$0.20 (event 2) and 6.4 $\pm$0.17 (event 3), for the youngest event were obtained. Incorporating the apparent slip-rate along with the length of surface rupture, gave M_w value of 6.5 $\pm$0.18.

The occurrence of surface rupture is found to be magnitude dependent (Avar and Hudyma, 2019). Based on 276 earthquakes, Lettis et al. (1997) stated that the probability of surface rupture for all types of faulting mechanisms increases from approximately 40% at M_w =5.9 to approximately 90% at M_w =7.2, and the probability of surface rupture decreases from 40% to 12% at M_w =5.0. The estimated magnitudes of the surface rupturing events along KHF range from 7.1 to 6.6, which suggest high probability of formation of surface ruptures during future earthquake events. This probability is very high along the KHF, as the presence of paleo-fault ruptures strongly controls the location of potential future surface ruptures (Avar and Hudyma, 2019). Bonilla (1979) also showed that of the 108 examples of worldwide historic surface ruptures, approximately 91% occurred on pre-existing faults, 8% were indeterminate in this regard based on available data and only 1% occurred where no fault existed previously.

The present study has yielded the moment magnitude (M_w) of the three Late Quaternary surface faulting events along KHF as shown in Table 8.1. The M_w values obtained from different equations as mentioned above, are remarkably consistent. The magnitude calculated using empirical relations give the maximum value of the expected earthquakes (Kanaori and Kawakami, 1996). It is believed that M_w values of the Late Quaternary 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 Late Quaternary surface faulting events show erosive contacts.

NEED FOR REAPPRAISAL OF EARTHQUAKE HAZARD

Earthquake damage to infrastructure solely due to surface rupture has started to receive greater attention (Kelson et al., 2001; Anastasopoulos and Gazetas, 2007; Faccioli et al., 2008). In dense urban environments, building damage can be traced along the surface rupture (Hart et al., 1993; Irvine and Hill, 1993; Nur et al., 1993; Lazarte et al., 1994; Lettis et al., 2000; Barka et al., 2002). Not all earthquakes cause surface rupture as the fault may not propagate to the ground surface even though the entire segment of the fault rupture is in the subsurface (Avar and Hudyma, 2019). However, repeated surface faulting events along the KHF during Late Quaternary is an exception in the case of seismically active Kachchh basin, which has witnessed several high magnitude earthquakes during the last 200 years and some events recorded in historic literature (Malik et al., 1999). The 1819 Allah Bund earthquake is the only known event in Kachchh that produced ~80 km surface rupture and extensive surface deformation, which occurred in the northernmost part of the basin (Oldham, 1926). Most recent 2001 Bhuj earthquake (M_w 7.7) did not produce surface rupture, even though its epicentre lay in a region of thick Quaternary cover (Mandal et al., 2003). It is presumed that the deeper focus of ~30 km was responsible for the inability of the displacement to reach the surface (Mandal et al., 2004). Moreover, detailed stratigraphic and neotectonic studies of the Late Quaternary deposits over the KMF also did not reveal any geological evidence of surface faulting (Chowksey et al., 2011; Maurya et al., 2017a). In this scenario, recurrent surface faulting events along KHF is interesting.

As Kachchh lies in a seismically active region, which belongs to the seismic zone V of the seismic zoning map of India, a number of seismic hazard analysis have been performed for the development of better mitigation strategies and an improved earthquake resistant design of civil structures. The seismic hazard assessments related to Kachchh basin are either performed following the probabilistic approach or deterministic approach. The assessments performed by workers such as Tripathi (2006), Yadav et al. (2008), Nath and Thingbaijam (2012) and Bashir and Basu (2018) followed the former approach of the two mentioned above, while Parvez et al. (2003), Shukla and Choudhury (2012), Chopra et al. (2012) and Mohan (2014) followed the latter.

In their work, Tripathi (2006), Yadav et al. (2008) and Bashir and Basu (2018) calculated the probability of earthquakes of M $\geq$ 5 for the whole region of Gujarat (Tripathi, 2006) and Kachchh (Yadav et al., 2008; Bashir and Basu, 2018) using same models (Weibull, Gamma, Lognormal) for the recurrence interval distribution of earthquakes. It has to be noted here that, the probability of earthquakes from Tripathi (2006), can neither be generalised for the whole region of Gujarat, nor can be compared with the Kachchh region independently, as Gujarat contains Kachchh as the most seismically active region as compared to Mainland Gujarat and Saurashtra regions, which show considerably low seismicity rates. Tripathi (2006) and Bashir and Basu (2018) used varying b-values of 0.72 and 0.69 respectively for the Gutenberg-Richter relationship for performing the PSHA for the Gujarat region and Kachchh region using same models for the recurrence interval distribution and arrived at significantly different results.

Nath and Thingbaijam (2012) performed the probabilistic seismic hazard analysis for India using logic tree framework of GMPE. The logic-tree framework is one of the probability enhancements, which are employed to correct some of the deficits in the probabilistic analysis. Such an approach to obtain earthquake ground motion groups for different models averages the different opinions received (Krinitzsky, 2002). In this approach, weights are assigned to each model according to the investigator's own opinion (Krinitzsky, 1998). The models used in this approach represent some unique data set, which in turn, provides erroneous and illogical results (Krinitzsky, 2002).

Also, the above studies rely on the Gutenberg-Richter *b*-line obtained from the earthquake frequency of occurrence curve (Gutenberg-Richter relationship) and GMPE (described above). This *b*-line obtained represents the rate of occurrence of earthquakes of different magnitudes (Krinitzsky, 1995); constructed from low magnitude earthquake data (as is the case of Bashir and Basu, 2018, who have used M $\geq$ 3.5) and is then projected to show the occurrence of large magnitude earthquakes, the data for which is barely considered. Any influx of new data (for e.g., a substantial earthquake occurred recently) in the b-line curve results into a large overall effect on the b-value (Krinitzsky, 1998). It is also known that the Gutenberg-Richter relation is only true for very large regions or world-wide data and is shown to be erroneous when used for small areas, crucial for engineering designs (Krinitzsky, 1993). Nonetheless, inclusion of the three high magnitude surface rupturing events in the earthquake catalog might alter the b-value

Tripathi (2006) for the Gujarat region and Yadav et al. (2008) for the Kachchh region used data corresponding to 24 events and 17 events of M $\geq$ 5 respectively in their studies to obtain the b-value using maximum likelihood method. From the results of Nava et al. (2017) it is clear that such small sample sizes as used by Tripathi (2006) and Yadav et al. (2008) give meaningless estimations of b-value. Nava et al. (2017) state that works dealing with b-value estimates from less than ∼12,000, ∼2000, and ∼500 magnitude data for precisions of 0.01, 0.025 and 0.50 magnitude units, respectively, are worthless. This is also supported by the fact that maximum likelihood method of Aki (1965) is the most accurate way to calculate b-value, which requires large data sets. Monte Carlo simulations and equations from Aki (1965) show that a minimum of 2000 earthquakes are needed to calculate b-value to within 0.05 at 98% confidence.

Moreover, the probabilistic method is believed to underestimate the possible accelerations close to major faults, which serve as the location of large earthquakes (Wyss and Rosset, 2013). Zuccolo et al. (2011) reported that the world seismic hazard map produced by the Global Seismic Hazard Project (GSHAP) underestimated the actual observed acceleration values by a factor of ~3, as detected in six cases. Furthermore, review of macroseismic intensities provided by GSHAP map (1999) revealed that observed intensity was larger by ~2.3 intensity units than that expected from the GSHAP map (Kossobokov and Nekrasova, 2012). It is also evident from the Table 10.1, that the probabilistic assessment has led to PGA value that lies in a broad range between 0.12g – 1.11g for the Bhuj city.

Parvez et al. (2003) predicted ground motion employing the preliminary source parameters of the 2001 Bhuj earthquake. As Kachchh basin characterized by multiple seismically active faults, the controlling seismicity of any region of Kachchh, especially Bhuj cannot be considered to be based on one single source zone. As the present study proves the generation of three high magnitude surface faulting events along the KHF (Tiwari et al., 2021), it becomes essential to consider it as a potential seismic source.

In the deterministic works of Mohan (2014), Chopra et al. (2012) and Shukla and Choudhury (2012), it is noticed that the input fault parameters used for KHF are completely different. In order to perform a correct seismic hazard analysis for an area, there shouldn't be different fault parameters considered for the same fault. As any meaningful seismic hazard analysis approach involves collection of appropriate input data (Klügel, 2008), the input fault parameters of KHF and other faults of Kachchh region should be fixed for use each time. This points towards performing proper seismic source characterization, which sometimes requires inputs from geological and geomorphological data, and then use those seismic source zone values in any calculations pertaining to the assessment of seismic hazard. The fault parameters deduced in the present study such as the length, displacement and slip rate using multi-proxy approach should be used as KHF fault parameters in any study dealing with the seismic hazard assessment.

Due to various limitations of probabilistic approach and inability of the deterministic approach to account for uncertainty, a combined use of both the approaches has found its application in a number of works (Mualchin, 1996; Anderson, 1997; Leyendecker et al., 2000; Bommer, 2002). The uncertainties associated with the seismic hazard analysis, mainly due to consideration of huge amount of data can be worked out or reduced by employing geological methods, commonly in the regions experiencing shallow seismicity and Quaternary tectonics (Wesnousky et al., 1984). Some of the essential information such as the location, dynamics, geometry, former measures of paleo-earthquake magnitude and their timing of occurrences are delivered by implementing geologic and geomorphic investigations in the advancement of earthquake modelling techniques (Field et al., 2014; Petersen et al., 2015). In addition to this, the topographical and geomorphological information obtained by describing significant but difficult to perceive Quaternary faults, may help in the reliable estimation, mitigation and preparation of response to devastating earthquakes in foreseeable future (Siame et al., 2002; Morell et al., 2020).