CONTENTS

Title	Page No.
Chapter – 1	
INTRODUCTION	1
THE RATIONALE	1
OBJECTIVES	5
STUDY AREA	5
Location	5
Physiography	5
Communication	6
Drainage	6
Climate	6
Flora	7
Fauna	7
People and occupation	8
APPROACH AND METHODOLOGY	8

Chapter – 2

REGIONAL STRUCTURE AND GEOLOGY	10
STRUCTURAL FRAMEWORK OF KACHCHH RIFT BASIN	10
STRATIGRAPHY OF KACHCHH BASIN	13
Mesozoic stratigraphy	13
Kachchh Mainland	14
Jhurio Formation	16
Jumara Formation	16
Jhuran Formation	16
Bhuj Formation	17
Pachham Island	17
Eastern Kachchh	18
Tertiary stratigraphy	19
QUATERNARY SEDIMENTS	22
Miliolite deposits of Kachchh	23
HISTORICAL AND RECENT SEISMICITY	24

Chapter – 3

METHODS	27
FIELD MAPPING	27
GROUND PENETRATING RADAR (GPR)	28
GPR data acquisition and data processing	29
MICROSCOPIC ANALYSES	31
Petrography	31
Scanning Electron Microscopy (SEM)	32
SEM sample preparation	33
SEM configuration	34
CALCULATION OF MOMENT MAGNITUDE (Mw)	36
MORPHOMETRIC MEANDER PARAMETERS	37
CHI (χ) ANALYSIS	38

Chapter – 4

LATE QUATERNARY SEDIMENTS ALONG KATROL HILL FAULT	
ZONE	41
PETROGRAPHIC CHARACTERISTICS OF MILIOLITE DEPOSITS	47
SCANNING ELECTRON MICROSCOPY (SEM) OF QUARTZ	
GRAINS OF MILIOLITES	50
Fluvial microtextures	50
Aeolian microtextures	54
Chapter – 5	
FIELD EVIDENCE OF LATE QUATERNARY SURFACE FAULTING	57
KHARI RIVER SECTION	59

Surface faulting events	62
Displacement and Slip rate	64
FIELD EVIDENCE FOR LATERAL EXTENSION OF SURFACE	
FAULTING	65
South of Bharasar	66
South of Bhujodi	67
East of Shiv Paras	68

Chapter – 6

GROUND PENETRATING RADAR STUDIES	70
GPR CHARACTERISATION OF QUATERNARY SEDIMENTS	73
Transect 1 – Wind gap in Katrol Hill Range	73
Transect 2 – Buried paleo-valley in Katrol Hill Range	76
GPR SURVEYS ALONG ACTIVE TRACE OF KATROL HILL	
FAULT	78
Transect 3 – South of Bhujodi	79
Transect 4 – Bharasar area	81
Transect 5 – Tapkeshwari area	83
Transect 6 – Ler area	84

Chapter – 7

MICROSCOPIC EVIDENCE OF LATE QUATERNARY SURFACE	
FAULTING	86
PETROGRAPHIC STUDIES OF SAMPLES FROM KHF ZONE	87
Fluvial miliolite deposits	87
Aeolian miliolite deposits	88
SCANNING ELECTRON MICROSCOPY (SEM) OF SAMPLES	
FROM KHF ZONE	90
SEM of quartz grains of fluvial miliolites along KHF zone	90
Excessive breakage	91
Striation and exfoliation	93
Adhering particles	94
Rolled quartz grains	94
SEM of quartz grains of aeolian miliolites along KHF zone	96
Excessive breakage	97
Striations and exfoliation	98
Fractured cleavage plates and silica precipitation	100
SEM of quartz grains located away from KHF zone	101

Chapter – 8

CHARACTERISATION OF KATROL HILL FAULT AS A POTENTIAL SEISMIC SOURCE 111

CALCULATION OF MOMENT MAGNITUDE (Mw)	111
Based on length of surface rupture	113
Based on displacement	115
Based on the length of surface rupture and slip rate	118
Chapter – 9	
DRAINAGE REORGANIZATION INDUCED BY SURFACE FAULTING	121
STRUCTURAL INFLUENCE ON GUNAWARI RIVER BASIN	121
ANOMALOUS CHANNEL MORPHOLOGY	124
LONGITUDINAL RIVER PROFILES	131
CHI (X) ANALYSIS	132
GEOMORPHIC EVIDENCE OF DRAINAGE REORGANIZATION	134
EVIDENCE OF DRAINAGE REORGANIZATION FROM GPR	
SURVEYS	137
PHASES OF DRAINAGE REORGANIZATION	138
Pre-miliolite phase	139
Syn-miliolite phase	140
Post-miliolite phase	143
Chapter – 10	
IMPLICATION FOR EARTHQUAKE HAZARD	145
EARTHQUAKE HAZARD IN KACHCHH BASIN	146
Probabilistic views	146
Deterministic views	147
NEED FOR COMBINED PSHA AND DSHA APPROACH IN	
КАСНСНН	149
INTEGRATING EARTHQUAKE HAZARD APPROACHES	
ALONG KHF IN REGIONAL PERSPECTIVE	154
Chapter – 11	
DISCUSSION	158
LATE QUATERNARY SURFACE FAULTING	159
Evidence from field studies	159
Evidence from GPR surveys	161
Microscopic evidence	163

Thin-section studies of fluvial and aeolian miliolite	
samples	163
Thin-section studies of the samples collected from the	
KHF fault trace	164
SEM studies	164
GEOMORPHIC EFFECT OF SURFACE FAULTING ALONG KHF –	
DRAINAGE REORGANIZATION	168
CHARACTERISATION OF KHF AS A POTENTIAL SEISMOGENIC	
SOURCE	172
NEED FOR REAPPRAISAL OF EARTHQUAKE HAZARD	174
Chapter – 12	
CONCLUSIONS	178
REFERENCES	183
LIST OF PUBLICATIONS	207

LIST OF FIGURES

Figure No.

Description

2

- Figure 1.1

 a. Location map. b. Map of Gujarat state showing climatic zones
 (source: imdpune.gov.in). Boxed area shows the area of
 Kachchh. c. DEM of Kachchh region showing major uplifts –
 Island Belt Fault (IBF), Gedi Fault (GF), South Wagad Fault
 (SWF), Kachchh Mainland Fault (KMF), Katrol Hill Fault
 (KHF), Vigodi Fault (VF) (based on Biswas, 1987) and
 epicentres of earthquakes from magnitude 3 to 7 (source:
 earthquake.usgs.gov). Boxed area with dashed line encloses the
 Kachchh Seismic Zone (KSZ) (based on Mandal and Chadha,
 2008). Boxed area with continuous line shows the area of
- Figure 2.1 Tectonic map of the western part of India showing pericratonic 11 rift basins with major structural lineaments and faults. Modified from Biswas (1987). Inset - location map of India. (JA-Jaisalmer Arch; RBA-Radhanpur Barmer Arch; SA-Saurashtra Arch; MR-Malwa Ridge; DT-Delhi Trend (maroon dashed lines); AT-Aravalli Trend (green dashed lines); ST-Satpura Trend (pink dashed lines); WCBMF-West Cambay Basin Margin Fault; ECBMF-East Cambay Basin Margin Fault; NPF-Nagar Parkar Fault; IBF-Island Belt Fault; KMF-Kachchh Mainland Fault; NKF-North Kathiawar Fault; WCF-West Coast Fault; NSF-Narmada Son Fault; NSGF-Narmada Son Geofracture). Modified from Biswas (1987); Merh (1995); Dasgupta et al., (2000) and Rastogi et al., (2013).
- **Figure 2.2** Geological map of Kachchh Basin showing major formations 14 and faults. Map redrawn by Patidar (2010) based on Biswas (1993).
- **Figure 3.1** Flowchart summarizing the approach and methods adopted in 28 the present study.
- **Figure 3.2** GPR data acquisition system showing the main components of 30 GPR system and configuration of subsurface reflectors. Modified from Neal (2004).
- **Figure 3.3 a**. Quartz grains mounted on SEM stage. **b.** SEM stage in the 33 column chamber.

- **Figure 3.4** An electron column showing the elements relating to the signals 34 from their emission till they are captured. The processing of signals takes place in the cabinet. Modified from Pereira-da-Silva and Ferri (2017).
- **Figure 3.5** Schematic figure of a conventional scanning electron 35 microscope. Modified from Zhou et al. (2006)
- Figure 3.6 Morphometric meander parameters: axis length (A), meander 38 neck length (L), river width (W), radius curvature (R), water flow length (S). Modified from Yousefi et al. (2016).
- Figure 3.7 Two river basins separated by a common drainage divide. a. The 39 existence of two channels in the state of disequilibrium. b. Evolution of both the channels from a state of disequilibrium to steady state by experiencing changes in the size and shape. The aggressor basin (towards left) shows lower steady-state elevation at the source, which consequently shifts the position of drainage divide towards the victim basin (right side). c. Evolution of the elevation of two channels meeting at the shared divide with respect to distance along the channel. Modified from Willett et al. (2018).
- **Figure 4.1** Generalised composite lithostratigraphy of exposed Quaternary 42 sediments along the Katrol Hill Fault zone. Modified from Patidar (2010).
- Figure 4.2 a. Geological map/DEM of the study area showing KHF and 43 mapped Quaternary sediments. Red coloured fault line shows active trace of the KHF based on present study. Note the sporadic nature of Quaternary sediment cover. S1-S9 and S1*-S6* mark the sampling location for microscopic studies. b. Representational N-S trending topographic profiles across the KHF zone showing the occurrences and stratigraphic set-up of Quaternary deposits in Katrol Hill Range (KHR) at Bharasar (a-a'), Tapkeshwari (b-b') and Bhujodi (c-c') and north of the Khatrod scarp (d-d'). Few sampling locations falling on the topographic profiles are also marked.
- Figure 4.3 a. Aeolian miliolite exposure found towards the north of 44 Bharasar dome. b. Aeolian miliolite deposits covering the foothill region north of the scarp found ~3 km south of Bhuj town.
 c. Close view of distinct aeolian cross-bedding displayed by a miliolite outcrop found south of Bharasar.

- Figure 4.4
 a. Thin and eroded layer of valley-fill miliolite deposited as 45 sheet miliolites over sandstone and shale sequences of Jumara Formation (older Mesozoic rocks) in the cliff section of a stream located north of Tapkeshwari road. b. Incised cliff section of the Gunawari river showing fluvio-aeolian miliolite deposits overlying the Mesozoic rocks. Note the variation in thickness of the valley-fill miliolite deposits.
- Figure 4.5 a. Close view of distinct horizontal sheets observed in valley-fill 46 miliolite deposits found in the cliff section of Gunawari reservoir towards the west of Ler area. b. Close view of fluvially reworked miliolites showing horizontal planar bedding and consisting of cobble sized clast.
- Figure 4.6 Thin-section photomicrographs of fluvially reworked (a to c) and aeolian miliolite deposits (d to f) sampled away from the KHF zone. a. (4x-XPL) Poorly sorted and sub-rounded to subangular detrital mineral grains are mostly quartz with calcareous foraminiferal tests. b. (10x-XPL) Point contact relation between the grains and recrystallization of calcitic cement forms microsparite between the inter-granular spaces. Rarely observed microcline pointing towards weak diagenetic activity. c. (10x-XPL) Occasional presence of an intact foraminiferal test. d. (2.5x-XPL) Well sorted and rounded to sub-rounded detrital quartz grains with peloid bioclasts and occasional shell fragments embedded in calcareous cement. e. (10x-XPL) Point contact relation between the grains and micro-sparite formation in the inter-granular spaces due to recrystallization of calcitic cement. f. (10x-XPL) Occasional presence of orthoclase feldspar indicating weak diagenetic activity. (D-Dissolution, MP-Micro-sparite, O- Orthoclase, P-Porosity, PE-Peloid, Q-Quartz, M-Microcline, SH-Shell fragments, F-Foraminiferal tests).
- Figure 4.7 SEM photomicrographs of representative quartz grains of 52 fluvial miliolite samples from the KHF zone displaying breakage patterns. a. Highly fractured quartz grain surface with unevenly broken edges and undergone solution action and silica precipitation over its rough and weathered surface. b. Unoriented surface fracturing of grain with prominent radial fractures marked by arrows. c. Breakage in the form of step-like fractures, approximately parallel to each other. d. Deeply inscribed arcuate and straight fractures in the form of steps observable on the conchoidal fracture planes of the grains. e.

Conchoidal fractures smoothed by solution action. **f.** Conchoidal fractures in shell-like breakage pattern (right side arrow) and sawtooth shaped fractures (left side arrow) with silica precipitation. **g.** chemically altered grain surface with v-shaped percussion marks. **h.** and **i.** Chemically altered and etched grain surface with crescentic gouges. **j.** Irregular pits and depressions on the grain surface. **k.** Solution action has filled the depressions and dissolved the protruding areas of the grain to produce elongated, linear and curved shallow depressions on the grain edge. **l.** Irregularly fractured surface with grooves and depressions with highly weathered grain edges.

- Figure 4.8 SEM photomicrographs of representative quartz grains of 53 fluvial miliolite samples from the KHF zone showing different types of silica precipitation. a. Uniform Si covering on an irregularly pitted and rough grain surface. b. Silica precipitation in the form of globules. c. Silica pellicle.
- Figure 4.9 SEM photomicrographs of representative quartz grains of 55 aeolian miliolite samples from the KHF zone. a. Grain with sharp edges and chemically weathered and rough surface with fresh fracture surface on its upper left portion. b. Fractures and depressions on the surface smoothed by solution activity and fresh fracture surface on the upper edge of the grain. c. Intensively fractured grain with rough surface and silica precipitation in the small grooves and a crack propagating from the lower edge of the grain. d. Linear set of sub-parallel fractures developed with a comparatively smooth surface and small conchoidal fractures. e. Small and large conchoidal fractures with numerous irregular depressions all over the grain surface with large breakage blocks. f. Rough surface with the presence of irregularly broken surfaces and upturned plates. Note the subrounded and bulbous edges of the grains. g. Straight and parallel fractures oriented perpendicular to curved fractures (lower left corner) and exposed quartz cleavage plates in the lower right portion. h. and i. Radial fractures on the fresh fractured surface. j. Numerous unoriented, irregularly shaped pits and etched surface resulting due to solution action on the grain surface. k. Alternating crest and trough pattern made of few linear and almost parallel ridges formed on the grain surface. I. Grain surface displaying numerous v-shaped and crescentic percussion marks, abrasion marks, silica precipitation and adhering particles.

- Figure 5.1 Katrol Hill Fault (KHF) plane exposed in the Mesozoic rocks a. 58 View of the fault trace of the KHF with scarp in the background found SE of Mankuva. Small arrow points to TV tower. b. Field photograph of the exposure of KHF. Note the south dipping fault plane and lithotectonic contact between the sandstone of Bhuj Formation and shale belonging to Jhuran Formation found south of Shiv Paras area. c. Field photograph of the KHF plane which marks the contact between the sandstone of Jhuran Formation and Bhuj Formation located near Ler village.
- **Figure 5.2** Geological map of the study area overlapped on DEM showing 60 the KHF, mapped Quaternary sediments, various geomorphic indicators of neotectonic reactivation of KHF, location of GPR transects (T1 to T6). Red coloured fault line shows active trace of the KHF based on present study. Note the discontinuous nature of Quaternary sediment cover.
- Figure 5.3 a. View of the exposure along the Khari river showing offsetting 61 in Late Quaternary sediments overlying the KHF. Note the extension of faults up to the surface. b. Interpreted overlay of the section of Khari river cliff section shown in (a). (a and b modified from Patidar et al., 2008). c. Close view of the basal part of the section showing KHF fault plane and associated displacement of bouldery colluvium (Unit-1). d. Close view showing Quaternary-Mesozoic litho-contact at the base of exposed cliff section. e. Close view of displacement (Event-1) of older colluvial wedges along F2 fault plane. The hanging wall block clearly shows truncation of granular layers against the F2 fault plane. f. Enlarged view of F2 fault plane, showing displacement of mixed gravelly and sandy beds (valley-fill miliolite) of Unit-2 which corresponds to Event-2. g. The successively younger beds of finely laminated miliolitic sands showing displacement of Unit-3 along the fault plane which is related to Event-3. The youngest sedimentary Unit-4, consisting of scarp derived colluvium sediments are also displaced by both the fault planes. (Modified from Patidar et al., 2008).
- Figure 5.4 Schematic sections (not to scale) showing the occurrence of 63 three events of Late Quaternary surface faulting along the KHF as observed in the Khari river section. Litho-units shown are the same as given in Figure 4.11a and b. All units show erosional bases suggesting post-faulting erosional intervals. Location of samples dated by Kundu et al. (2010) are also shown. **a.** Deposition of bouldery colluvium (unit A) unconformably over

the Mesozoic rocks overlapping the KHF. Note the steeply southward dipping reverse movement along KHF. **b.** Deposition of gravelly sand (Unit B) over boulder colluvium and offsetting of both units (A and B) due to occurrence of surface faulting Event-1. During this event, the KHF splays into two planes (F1 and F2) as a consequence of its upward propagation in the overlying unconsolidated Late Quaternary sediments. **c.** Deposition of coarse sand (Unit C) and stratified miliolitic sand (Unit D). Comparatively higher thickness of these units is observed in the downthrown block. Deposition of this unit was followed by the occurrence of second surface faulting event (Event-2) along the KHF. **d.** Erosional interval followed by the deposition of the youngest Unit E comprising scarp-derived colluvium. This was followed by the surface faulting Event-3.

- **Figure 5.5** Slip history diagram of the Late Quaternary surface faulting 64 events along KHF consisting of three paleo-earthquakes and showing two complete (closed) seismic cycles and two partial (open) seismic cycles. Diagram drawn as described by McCalpin (2009).
- Figure 5.6 a. Tectonically deformed aeolian miliolite deposits found 67 towards the south of Bhujodi. Note the abrupt steepening of the foresets of the cross bedding along the fault. The KHF scarp is seen in the background. b. Almost vertical, south dipping stratification of aeolian miliolite deposits overlying the KHF near Bhujodi.
- **Figure 5.7** KHF plane exposed as a contact between the Bhuj Formation 68 and aeolian miliolite deposit found east of Shiv Paras. Note the absence of macroscopic deformation in the outcrop.
- **Figure 6.1** CMP radargram recorded using 40 MHz bi-static antenna 71 configuration. Derived semblance plot is shown on the right side.
- Figure 6.2
 a. Processed GPR profile across the wind gap acquired using 75 200 MHz shielded antenna. Colour variation is a function of amplitude of radar waves in the subsurface.
 b. Processed GPR profile showing various radar facies. The radar facies are described in Table 6.1.
 c. Interpreted GPR profile in wiggle format. Axis on left side shows penetration depth in meters and on right site two-way travel time (TWTT) in ns is denoted. The upper axis shows the length of profile in meters. Note the broad bedrock valley filled with aeolian and reworked Late Quaternary

miliolite sediments. The reworked miliolites are attributed to the paleo-Gangeshwar river that flowed northward through the wind gap. The prominent erosional truncation surface closer to the surface marks the end of fluvial activity in the channel indicating loss of catchment of the paleo-Gangeshwar river due to river diversion induced by tectonic tilting as explained in the text. The major bounding surface of wind gap is highlighted by thick red lines in Figures b and c. Note that at the base, the sedimentbedrock interface is poorly defined, marked by red dashed line. The erosional truncation surface is denoted by green continuous line, conformable contact in between the Quaternary deposits is marked by green dotted line and internal bounding surfaces in between the radar facies are marked by black continuous/dotted lines in Figures b and c.

- Figure 6.3 a. Processed GPR profile across the right bank of Gangeshwar 77 river located in the buried paleo-valley acquired using 200 MHz shielded antenna. Colour variation is a function of amplitude of radar waves in the subsurface. b. Processed radargram showing various radar facies. The radar facies are described in Table 6.1.
 c. Interpreted GPR profile in wiggle format. Note the sloping bedrock valley filled with aeolian and reworked Late Quaternary miliolite sediments. The prominent erosional truncation surface closer to the surface marks the end of fluvial reworking of miliolite sediments indicating due to river diversion after the depositional phase of miliolites. Follow Figure 6.2 caption for interpretation of radargrams.
- 80 Figure 6.4 a. Processed GPR profile acquired from the Katrol Hill Fault (KHF) zone in front of the scarps. The general high amplitudes in the upper part of the radargram are from the Late Quaternary aeolian miliolite deposits overlying the fault line. b. Processed radargram showing the various radar facies details of which are provided in Table 6.1. c. Interpreted radargram in wiggle format. Note the largely aeolian nature of the sediments reflected by the large-scale cross stratification. Also notice the high angle reverse nature of the KHF and its extension up to the surface offsetting the overlying sediment cover. The large scale aeolian cross stratification also gets markedly steeper along the fault plane. Note that the subsidiary antithetic and synthetic slip planes (marked by black and red dotted lines in Figures b and c, respectively) in the hanging-wall of KHF show a reverse slipsense while those in the Mesozoic rocks in the footwall of KHF show a normal slip-sense.

- Figure 6.5 a. 200 MHz processed GPR profile in NNW-SSE direction 82 acquired from south of Bharasar village. Arrows point to the onlapping wedge out and deformed geometry of near surface reflectors. The high amplitude continuous reflectors between 50 and 80 ns show erosional cut and fill geometries corresponding to the deposition of valley filled miliolite/younger sediments. b. Interpreted section of the GPR profile. The features are characterized on the basis of specific reflection pattern and amplitude variation. Note the changes in reflection pattern due to various geological features and reflectors offsetting along the fault plane.
- **Figure 6.6 a.** 200 MHz processed GPR profile in N-S direction obtained from Tapkeshwari area. **b.** Interpreted line drawing section based on GPR profile shown in (a). Distinct changes in the reflector continuity and abrupt truncation along a plane is noticed between 10 and 15 m distance. The reflector offsetting, prograding colluvium wedges, younger channel cut and fill features are shown. The Quaternary-Mesozoic interface near 50–75 ns is marked based on reflector geometry/pattern and amplitude contrast. Based on deformed reflector and their abrupt truncation, the subsurface geometry of KHF is marked, which indicates gentle south dipping reverse fault plane that became almost vertical at depth.
- Figure 6.7 a. 200 MHz processed GPR profile in N-S direction obtained 85 near Ler area. Note the offset and change in energy of reflectors across the fault plane (marked by dotted lines) which clearly depicts the changes in lithology; towards the north is the Bhuj formation showing continuous and high energy reflectors while the low energy discontinuous reflectors characterize the Jhuran formation. b. Interpreted line drawing section of GPR profile showing KHF plane based on reflector displacement and truncation along a plane. A distinct change in reflectors amplitude and presence of various deformational features in the upper section of the profile helps to define Quaternary-Mesozoic interface at ~50-60 ns. At ~25 ns it is difficult to outstretch the KHF plane up to the surface in profile due to highly rugged topography along GPR transect line and poor reflectivity from shallow section.
- Figure 7.1 Thin-section photomicrographs of fluvially reworked miliolite 88 deposits sampled from the KHF zone. **a.** and **b.** Microcracking along grain boundaries of detrital quartz grains. **c.** Slight

orientation of constituent mineral grains and bioclasts. **d.** Recrystallization in the form of radial extinction observed in allochem grains. **e.** Micro-sparitization of calcitic cement with development of calcitic micro-fibres along the grain boundaries. **f.** Polycrystalline quartz grain showing undulose extinction. (D-Dissolution, MP-Micro-sparite, O- Orthoclase, P-Porosity, PE-Peloid, Q-Quartz).

- Figure 7.2 Thin-section photomicrographs of aeolian miliolite deposits 89 sampled from the KHF zone. a. Fault perpendicular thin-section showing microfractures in the angular to sub-angular detrital quartz grains. b. Microfracturing of peloid bioclast and detrital grains. c. Fault parallel thin-section showing well sorted, angular to sub-angular and slight orientation of the constituent mineral grains. d. Recrystallization and microcracking of the detrital quartz grains. e. Recrystallization along the grain boundaries of quartz grains and peloid bioclasts. Note the calcitic microfibers developed on the peloid grain boundaries. f. Polycrystalline quartz grain showing undulose extinction. (D-Dissolution, MP-Micro-sparite, O- Orthoclase, P-Porosity, PE-Peloid, Q-Quartz).
- Figure 7.3 SEM photomicrographs of representative quartz grains of 92 fluvial miliolite samples from the KHF zone showing excessively fractured nature. a. Highly abraded surface with a prominent crack along grain boundary. **b**. Abraded surface with exfoliated sheet and meandering ridge pattern. c. Prominent surface cracks developed on an abraded grain surface. d. Cracks and fractures on smoothed grain surface due to solution activity. e. Fractured grain surface with small and large, sub-parallel conchoidal fractures smoothened by solution action and silica precipitation. f. Sub-angular grain with numerous cracks on the surface with deeply engrossed straight and curved grooves on the fresh fracture surface. g. Triangular faceted grain with fresh fractured smooth surface. h. Fresh fractured smooth surface of the grain. i. Chemically etched and highly abraded grain surface, deeply engraved grooves and upturned plates.
- Figure 7.4 SEM photomicrographs of representative quartz grains of 93 fluvial miliolite samples from the KHF zone showing prominent striations (a to f) and exfoliation (g to i) features marked by arrows. Note that striations do not fully cover the grain surfaces (a to f) in all the grains except in e. Exfoliation on the grain surfaces (g to i) is seen in patches. Also note the fractured nature of the grains and grain boundaries.

- **Figure 7.5** SEM photomicrographs of representative quartz grains of 95 fluvial miliolite samples from the KHF zone showing the presence of adhering particles on the grain surfaces. Note the excessively fractured nature of the grains and broken grain boundaries.
- **Figure 7.6** SEM photomicrographs of representative quartz grains of 96 fluvial miliolite samples from the KHF zone consisting of rolled quartz grains (a to f) and euhedral crystal (g to i). Note the presence of abraded surface of the grains. Faint striations on the surface can be seen in (f).
- Figure 7.7 SEM photomicrographs of representative quartz grains of 97 aeolian miliolite samples from the KHF zone showing fractured nature (marked by arrows) of the grains. a. Excessive silica precipitation with abrasion fatigue. b. Silica precipitation covers the microtextures present on whole of the surface. c. Smoothed quartz cleavage plates and elongate depressions resulting due to fracturing. d. Upturned plates are present on the upper and lower edges of the elongated quartz grain and shows smoothed left boundary due to solution action. e. Fresh fractured and abraded quartz surface with deeply engrossed conchoidal fractures surrounded by upturned plates in lower left portion and silica precipitation over the abraded surface of the grain. f. Fresh fractured quartz grain depicting radial fractures and sharp edges. g. Elongated grain with sub-angular edges and v-shaped fractures on the top of the grain with irregular depressions and upturned plates on the grain edges. h. Small arcuate step like fractures grade into straight steps of relatively larger size. i. Chemically etched grain boundary with parallel to sub-parallel fractures on the fresh fractured grain surface. Note the fractured surfaces and excessive silica precipitation on the grain surfaces.
- Figure 7.8 SEM photomicrographs of representative quartz grains of 99 aeolian miliolite samples from the KHF zone showing striated, excessively broken and exfoliated grain surfaces (marked by arrows). a. The grain shows distinct striation marks on the surface. b. Striation marks are seen overlapped by silica precipitation. c. Exfoliated sheet on the surface which exposes the underlying cleavage plates. d. Abraded edges with exposed cleavage plates. e. Quartz grain with bulbous edges and rough surface with silica precipitation and upturned plates. f. Euhedral quartz grain with traces of silica precipitation. g. Euhedral quartz grain with rounded and weathered edges. h. Excessively

broken grain surface (sawtooth fractures) and highly fractured cleavage plates. **i.** Highly eroded grain surface showing exfoliation. Note the presence of silt sized adhering particles on the grain surfaces.

- Figure 7.9 SEM photomicrographs of representative quartz grains of 100 aeolian miliolite samples from the KHF zone. a. and b. Large breakage block exposing fresh fractured surface and typical v-shaped fracture. c. Excessively broken quartz cleavage plates. d. Deeply engrossed small and large depressions or solution pits developed due to solution action on a weathered surface. e. Fractured surface displaying parallel fractures and exfoliation surface. f. Weathered surface showing silica precipitation and development of silica pellicle.
- **Figure 7.10** SEM photomicrographs of representative quartz grains of the 102 samples away from the KHF zone. a. Breakage in the form of conchoidal fractures. b. Sub-conchoidal fractures and solution activity giving rise to pitted appearance on the surface. c. Abraded grain edges with small conchoidal fractures with relatively smooth surface and limited silica precipitation in small pits created due to solution action. d. Numerous upturned plates in the upper portion of the grain surface with small depressions and less weathered lower portion. e. Curved grooves are seen covered by silica precipitation towards the upper right portion of the grain. f. Small and large conchoidal fractures and grooves with limited silica precipitation. g. Solution pits observed throughout the abraded grain surface. h. Abraded upper portion of the grain surface with sharp lower edge and limited silica precipitation. i. Weathered grain surface with small curved fractures. Note the absence of excessive breakage and striated surfaces.
- Figure 7.11 SEM photomicrographs of representative quartz grains of the 103 samples along the segment of KHF from Deshalpar to Bharasar and from Ler to Wavdi. Grain surfaces in (a to d) show abrasion features like chemical etching due to variable amounts of solution action and the presence of upturned plates. e. and f. show relatively larger solution pits on chemically etched surface. g. Silica precipitation in the depressions formed on the grain surface due to breakage or solution action. h. Set of parallel fractures modified and smoothened by solution action.

- Figure 9.1 DEM of Katrol Hill Fault (KHF) zone (modified after Patidar et 122 al., 2008). Note the rugged hilly topography of the Katrol Hill Range bounded by the KHF in the north. Also seen are the north and south-flowing drainage lines. Boxed area in dashed lines show the area covered in Figure 9.2a. Red colour indicates Late Quaternary miliolite deposits.
- Figure 9.2 **a.** Map of the Gunawari river basin and Gangeshwar river basin. 123 Note the anomalous nature of the Gunawari basin. Yellow colour denotes Late Quaternary miliolite sediments. The miliolite deposits occur along the valley including paleo-valley and wind gap in the Katrol Hill range and along the KHF zone. Thin white line shows the orientation of topographical sections - a-a', b-b', c-c'. b. N-S topographical section showing structurally controlled geomorphic setting of the area. Note the geomorphic contrast between the hilly topography of the Katrol Hill Range and the rocky plain in the north controlled by the KHF. c. NE-SW topographical section passing through the Gunawari river, wind gap and the KHF zone. Yellow colour indicates Late Quaternary miliolite deposits. d. E-W topographical section showing rugged topography, Gangeshwar river located in miliolite filled buried paleo-valley and Gunawari river in the saddle zone. (TF-Transverse fault).
- Figure 9.3 a. Satellite image of the area showing structurally controlled 125 courses and anomalous channel characteristics of the Gunawari and Gangeshwar rivers (source: https://earth.google.com/). Major features and location of the field photographs included in Figure 4 and 5 are indicated. K1, K2 and K3 show the location of knickpoints. 1-5 are the anomalous channel segments of the Gunawari river. 1 – E-W trending incised meandering channel in the upstream reach of the Gunawari river. Note that most of the cliffs are formed on the southern bank of the river. 2 - V'shaped bend of the Guawari river. Note the tributary stream joining at the apex of 'V'-shaped bend. The eastern arm of the 'V'-shaped bend is in alignment with the trend of the tributary stream. 3 - 'S'-shaped bend of Gunawari river. The bend is formed by two oppositely oriented right-angled bends. 4 – E-W trending straight channel after the Gunawari river emerges out of the 'S' -shaped bend. 5 - Channel of Gunawari river in the saddle zone to the east of Ler dome. b. Downstream view of the narrow, incised channel of the Gunawari river in its upper catchment in back-valley. The cliffs expose Late Quaternary miliolite sediments with Mesozoic rocks at the base. Note the

absence of channel alluvium. c. View of the anomalous 'V'shaped bend developed in Mesozoic rocks overlain by miliolites. The tributary coming from south and joining at the bend is also shown. d. Upstream (southward) view of the eastern arm of the 'V'-shaped bend showing zone of falls with multiple falls/knickpoints (K1). Location of the tributary indicated in (c) is also shown. e. Upstream (westward) panoramic view of the Gunawari channel. Thick white arrow points to the direction of buried paleo-valley towards north. The extremely narrow, straight, shallow eastward flowing channel in the foreground is formed after the river abandoned the paleo-valley due to river diversion. f. Downstream view of the eastward flowing straight channel of Gunawari river as it enters the 'S'-shaped bend. The channel is formed along the soft shales exposed in the cliff at the bend seen at the far end. The ~10 m height of the cliff is a reflection of the elevation of the drainage divide breached during phase of drainage reorganization. Also note the knickpoint (K2) at the 'S'-shaped bend. g. South facing view showing the 'S'-shaped bend showing narrow bedrock channel and knickpoints (K2, K3). h. Eastward (downstream) view of the narrow, straight channel of the Gunawari river after the 'S'shaped bend shown in (f). Note the south dipping Mesozoic rocks (Jumara Formation) comprising the southern limb of the Ler dome.

- Figure 9.4
 a. Close view of the incised river cliffs showing aeolian and 127 reworked Late Quaternary miliolite deposits. b. Eastward view of the wind gap. The light-coloured flat surface is developed over the Late Quaternary miliolite deposits in the wind gap. The rocky hill slope at the far end is comprised of Mesozoic rocks of the Ler dome. c. Northward view of the buried paleo-valley. Location of the channel of northward flowing Gangeshwar river is indicated. Note the nature of the rocky plain in the distant background visible through the buried paleo-valley. Location of photographs in b and c are shown in Figure 9.3a.
- **Figure 9.5** Map showing channels of Gunawari and Gangeshwar rivers 128 with channel segments and reaches. Morphometric data generated for the channel reaches is shown in Table 9.1.
- **Figure 9.6 a.** Longitudinal river profile of the Gunawari river. Location of 131 characteristic channel reaches and anomalous segments described in the text are indicated. K1, K2 and K3 denote knickpoints in the river profile. The point on the long profile closest to the headwaters of the Gangeshwar river is marked as

P. Note the abrupt break in channel gradient in the anomalous 'V' and 'S'-shaped bends. The Marutonk dungar Fault does not show any effect on the river profile indicating its inactive nature. **b.** Longitudinal river profile of the Gangeshwar river. Note the origin of Gangeshwar river at the margin of the floor of the buried paleo-valley. The elevation difference of the floor of the wind gap and the present-day channel of Gunawari river is also shown. T1, T2 and T3 indicate the location of the transects of GPR profiles shown in Figures 6.2, 6.3 and 6.4.

- **Figure 9.7 a.** Chi (χ) map of Gunawari and Gangeshwar river basins. Note 133 the high chi (χ) values in the source region of Gunawari river and almost identical values across the divide between the two rivers. **b.** Chi (χ) plot of the Gunawari river channel from origin to its confluence with Dharawa river. Note the abrupt slope variation that corresponds with the anomalous channel reaches and the KHF zone.
- Figure 9.8 a. Reconstructed paleo-drainage lines inferred from geomorphic 136 evidences. Note that the paleo-Gangeshwar was a larger river while the paleo-Gunawari was a short river that drained the area around the eastern fringe of Ler dome. This drainage existed prior to and during the deposition of phase of miliolite lasting up to ~40 ka B.P. This drainage set up was reorganized in the last ~30 ka B.P. due to tectonic tilting attributed to surface faulting along KHF. b. Map showing present day drainage lines in the study area. The channel segment of Gunawari river shown in black dashed line was formed due to reorganization of drainage in last ~30 ka B.P. The channel marked dark by red dots indicates the drainage line (paleo-Gangeshwar river) that existed previously during and before the deposition of miliolite sediments as shown in (a).
- Figure 9.9 Schematic models showing stages of drainage rearrangement in 141 the study area (a-c) and formation of the anomalous 'V'-shaped bend (d). a. Drainage set up prior to the deposition of Late Quaternary miliolite sediments. Note the absence of deposits younger than Mesozoic rocks. Dotted lines indicate inferred drainage divides. paleo-Gangeshwar and paleo-Gunawari rivers are the ancestors of present-day Gangeshwar and Gunawari rivers respectively. Note the Tributary 1 and Tributary 2 meeting the paleo-Gangeshwar river. b. Drainage set up during the Late Quaternary depositional phase of miliolite sediments. Notice the deposition aeolian miliolite sediments in the river channels including wind gap and in front of north facing KHF scarps.

Rivers continued to maintain their courses (denoted by dashed line) during this phase resulting in short and episodic reworking aeolian miliolite sediments. c. Phase of drainage of rearrangement after the depositional phase of miliolite (last ~30 ka B.P.). Dotted line denotes the present-day drainage divides. Multiple surface faulting events along the KHF under compression led to uplift of the Katrol Hill Range in tilted manner which triggered drainage rearrangement. Southward tilting caused greater uplift of the wind gap which led to beheading paleo-Gangeshwar river. Channel segment of the catchment was diverted eastward along the easier path of the E-W strike of the Mesozoic rocks forming straight E-W oriented channel up to 'S'-shaped bend through reversal of Tributary 2 and top-down (TD) process. The paleo-Gunawari at the eastern margin of Ler dome extended its course upstream through along strike headward erosion towards east along the strike forming E-W trending straight channel. Both straight channels oriented in same direction and progressing towards each other joined up producing the 'S'-shaped bend which formed the capture point. **d.** Model depicting the formation of the anomalous 'V'-shaped bend during the phase of drainage realignment in the last ~30 ka B.P. Prior to drainage realignment, the river flowed in a straighter path along the wind gap marked as 'W'. Southward tectonic tilting due to surface faulting along the KHF forced the river to flow southward through top-down process (TD), forming the western arm of 'V'-shaped bend. The new channel met up with the pre-existing tributary (Tributary 1) that flowed northward after arising from the Marutonk dungar hill located in the south. The development of 'V'-shaped bend is therefore attributed to the drainage rearrangement that was strongly influenced by tectonic activity and the reach specific conditions i.e., availability of the channel of Tributary 1.

LIST OF TABLES

Table No.	Description	Page No.
Table 2.1	Stratigraphic set-up of Kachchh basin (after Biswas, 2016a).	15
Table 2.2	Tertiary stratigraphy of Kachchh basin (after Biswas, 2016a).	20
Table 5.1	Various parameters of Late Quaternary surface faulting events along the KHF as deduced in the present study.	65
Table 6.1	Details of the observed radar facies and their geological interpretation. Radar facies nomenclature is based on amplitude response, continuity and geometry of reflectors.	72
Table 7.1	Summary of observations and interpretation from field studies, optical microscopy and scanning electron microscopic (SEM) analyses of samples collected along and away from the KHF. Location of samples are shown in Figure 4.2a.	104
Table 8.1	Empirical relationships used in the present study for calculating magnitude of Late Quaternary surface faulting events using various input parameters.	113
Table 8.2	Calculated Mw values of the Late Quaternary surface faulting events along the KHF using empirical relationships shown in Table 8.1.	120
Table 9.1	Morphometric parameters of the Gunawari and Gangeshwar rivers. The channel segments and reaches are shown in Figure 9.5.	130
Table 10.1	PGA hazard values for the Bhuj city in Gujarat worked out by different workers.	151