

List of Figures

Title	Page No.
Chapter 1	
Fig 1.1 Location Map of the study area. Star sign in the figure shows the sites at which the palaeoseismological investigations were carried out.	4
Fig 1.2 Figure showing the general topography of Kachchh region	6
Fig 1.3 Rainfall data of last 50 years for the Kachchh region	8
Fig 1.4 Figure showing the population density of different towns of Kachchh district (source: Kachchh Gazetteer, 1971)	11
Fig 1.5 Communication Map of Kachchh region	12
Fig 1.6 Generalised geological map of the study area (after Biswas and Deshpande, 1970)	13
Chapter 2	
Fig 2.1 Tectonic and structural set-up of Gujarat (after, Biswas, 1987 and Merh, 1995)	17
Chapter 3	
Fig 3.1 Generalised geological map of Kachchh region (after Biswas, 1982)	24
Fig 3.2 Tectonic map of Kachchh region (after Biswas and Deshpande, 1977)	33
Fig 3.3 Structural Map of Kachchh region (after Biswas, 1987)	34
Fig 3.4 Geological cross-section across Kachchh Mainland (after Biswas, 1987)	36
Fig 3.5 Map showing major and Minor lineaments and faults	38
Fig 3.6 Generalised Geomorphic map of Kachchh Showing different geomorphic zones	42
Fig 3.7 Generalised drainage map of Kachchh	45
Chapter 4	
Fig 4.1 Structural map of the study area showing variety of structural features mapped during the field study (modified after Hardas, 1969)	49
Fig 4.2 Rose plot showing the strikes of observed fault population on Central Kachchh Mainland	51
Fig 4.3a Rose plot showing the strikes of the normal faults encountered to the north of Katrol Hill Fault, b) Rose plot showing strikes of the observed normal faults to the south of Katrol Hill Fault, note the distinct presence of the E-W trend to the south of KHF	52
Fig 4.4a Stereographic projections showing the attitudes of major normal faults to the north of Katrol Hill Fault, b) Stereographic projections of the observed major normal faults to the south of Katrol Hill Fault (only those faults are plotted where the dip of the fault and the dip-direction are precise)	53
Fig 4.5 Graph showing the displacement profiles of two mesoscopic faults observed near Bhuj, note the general bell shaped nature of the profile indicating the maximum amount of displacement near the center.	54

Fig 4.6a. A Mesoscopic fault scarp exposed to the north of Bhuj	56
Fig 4.6b Fault scarp showing the segmented nature. The fault striking N20°E dies out and reappears with a change in the direction of N45°E. (site studied some 7 km North of Bhuj)	56
Fig 4.7 Deformational banding observed in Bhuj sandstone south of Bhuj	57
Fig 4.8 Line drawing showing different geometries forming on account of variable slip along a fault plane (after Peacock and Sanderson, 1994a)	59
Fig 4.9 Black and white image of an extensional bending observed in Bhuj sandstone, note the refraction of fault plane at the junction of two beds (site: 3 km south of Bhuj)	60
Fig 4.10a Photograph showing a well developed overstep and a bend in Bhuj sandstone (site: 7 km WNW of Bhuj)	61
Fig 4.10b Black & White image of photograph showing the well developed extensional overstep and a bend	61
Fig 4.11a Photograph showing well developed downward warping and upward warping on account of normal fault propagation	62
Fig 4.11b Black & White image of an extensional bend seen in Fig 4.11a	62
Fig 4.12a Photograph showing pull-apart structure observed 5 km south of Bhuj	63
Fig 4.12b Line drawing of the pull apart structure observed 5 km south of Bhuj	64
Fig 4.13a Photograph showing contractional bending 7 km WNW of Bhuj	65
Fig 4.13b Black and White image of contractional bending, note the thinning of beds near fault plane	65
Fig 4.14a Photograph showing a clear flat on to a ramp structure on a very small scale	66
Fig 4.14b Black & White image of flate and ramp structure observed 7 km WNW of Bhuj	67
Fig 4.15 Photograph showing a clear contractional bend wherein a near 50% thinning has taken place, note the radial fracturing emerging from all the sides of the plane	67
Fig 4.16 Photograph showing a fault splay at a location near Bhuj	68
Fig 4.17 Photograph showing a number of small faults exposed in a quarry section about 12 km south of Bhuj	69
Fig 4.18 Photograph showing a number of small faults in association with two major conjugate faults exposed in a quarry section near Bharapar	70
Fig 4.19 Photograph showing a number of small fault segments emerging out of a single fault resembling an inverted flower structure of Sylvester (1988) on small scale.	70
Fig 4.20 Rose plot of reverse faults encountered to the south of Katrol Hill Fault. Important to note is that no exposure of a reverse fault was encountered to the north of Katrol Hill Fault	71
Fig 4.21 Line drawing of a reverse fault parallel to bedding plane observed in the vicinity of Katrol Hill Fault	72
Fig 4.22 Line drawing of an apparent imbricate system of sub-parallel reverse faults observed near Hamadra Talai, about 11 km south of Bhuj	73
Fig 4.23 Rose plot of strike slip faults encountered within the study area. Important to note is that almost all the faults observed have the trend transverse to the major Katrol Hill Fault	74
Fig 4.24 Black & White image of a small strike slip fault displacing a fossil Belemnite, encountered about 7 km south of Bhuj.	75
Fig 4.25 IRS-FCC image showing a left lateral strike slip fault displacing the late	76

Tertiary sediments, WSW of Bhuj	
Fig 4.26 Line drawing of an ideal fault propagation fold (after Suppe and Medwedeff, 1990)	81
Fig 4.27 Map showing the locations where good folding exposures were observed	81
Fig 4.28 Photograph showing an exposure scale fault propagation fold	83
Fig 4.29 Photograph showing fault propagation fold developed along a Bedding parallel thrust.	83
Fig 4.30 A well developed fault propagation fold in the vicinity of Katrol Hill Fault	84
Fig 4.31 Exposure scale fault propagation folds observed on way to Jadura Mota, note the wedges emerging along sub parallel thrust faults	85
Fig 4.32 Photograph showing mesoscopic folding near Anjar	86
Fig 4.33 Photograph showing gentle folds exposed in late Tertiary rocks near Dumra	87
Fig 4.34 Photograph showing conspicuous folding in siltstones of late Tertiary age (site: 4 km east of Naliya)	87
Fig 4.35 Photograph showing gentle warps in Miliolitic rocks exposed in the northern flank of Katrol Hill Fault	88
Fig 4.36 Map showing the joint orientations at various locations within Central Kachchh Mainland (only significant locations are shown)	90
Fig 4.37 Photograph showing an array of systematic joint sets observed 6 km south of Bhuj.	92
Fig 4.38a Photograph showing well developed orthogonal sets of joints in Mesozoic rocks in the near vicinity of Katrol Hill Fault	92
Fig 4.38b Photograph showing prominent orthogonal sets of joints about 6 km south of Madhapar	93
Fig 4.39 Photograph showing a fracture grid lock at a location near Kukma.	94
Fig 4.40 Formation of different joints sets, i.e. one perpendicular to the hinge of the fold and the other parallel to it (after Hancock, 1985)	95
Fig 4.41a Photograph showing a view of the different types of Liesegang structures encountered in the field (Loc: 5 km north of Bhuj along Bhuj-Khavda road)	97
Fig 4.41b Photograph showing a close up view of simple Liesegang structure, note the deviation of the Liesegang lamellae around a concretion (Loc: About 5 km NW of Bhuj on Bhuj-Kodki road)	98
Fig 4.42a Photograph showing the simultaneous occurrence of joints and Liesegang structures	99
Fig 4.42b Black & White image demonstrating the relationship of joints and formation of Liesegang structures (inset block is magnified (1.6x) to show the initiation of Liesegang structure)	100
Fig 4.43a A close up view (from top) of a compound Liesegang block showing the relicts of the preexisting structure (the sample is baked and polished for more clarity)	101
Fig 4.43b A line drawing showing the interference of the joint sets responsible for the genesis of the compound structure. The drawing diagrammatically demonstrates the evolution of the compound Liesegang block (B) from the preexisting simple one (A). OJ is the older joint polygon which served a conduit for the solutions involved for the formations of an earlier Liesegang pattern (reconstructed) and YJ is the subsequent joint polygon	101

responsible for the modification of the preexisting Liesegang pattern.	
Fig 4.44a Photograph showing the compound Liesegang structures at study site on Bhuj-Kodki road	102
Fig 4.44b A line drawing showing the superimposition of subsequent joint sets responsible for the modification of the preexisting structures (OJ – older joint polygon, RJ – a joint set showing no signs of weathering, which is seen to cut through the compound structures and hence considered to have developed in recent times, YJ – a joint polygon responsible for the modification of the already existing structures which is subsequent to OJ but has formed prior to RJ	103
Fig 4.45 Lineament map of study area	105
Fig 4.46 Graph showing the Length-Azimuth relationship of the lineaments	106
Fig 4.47 Lineament rosettes showing spatial distribution	108

Chapter 5

Fig 5.1 Generalised Geomorphic map of Central Kachchh Mainland showing two prominent hill ranges (i.e. Katrol Hill Range (KHR) and Sanosra Dungar Range (SDR)	113
Fig 5.2 Drainage map of Central Kachchh Mainland	115
Fig 5.3a. Earlier drainage that existed before the major uplift event, b) The post uplift scenario of the drainage behaviour of Central Kachchh Mainland	117
Fig 5.4a. Photograph showing the ponding condition to the north of Bhuj in the Khari river channel	118
Fig 5.4b. The conditions of flow diversion observed near Godpar in a small tributary of Nagavanti river	119
Fig 5.5 The Sketch showing the development of successive terraces exposed within the Katrol Hill Zone (T1- Strath Terrace, T2- Alluvial fill Terrace, T3-Alluvial fill Terrace)	121
Fig 5.6 Three paired terraces within the Katrol Hill Zone (Loc. 6 km south of Bhuj, along the Bhuj-Mandvi Road)	122
Fig 5.7 Terracing sequence to the north of Katrol Hill Fault	123
Fig 5.8 Raised beach along Mandvi coast	125
Fig 5.9. Drainage morphology of south flowing Rukmavati and Kharod rivers originating from southern flank of Katrol Hill. Note the intense gully erosion marking the course of the channels	126
Fig 5.10 Morphological drainage network of north flowing streams marked by their structure controlled deeply entrenched courses and sudden high angle deflections	127
Fig 5.11 Formation of Gorge along the Khari river near Kodki (Loc: 9 km west of Bhuj)	128
Fig 5.12 Palaeochannel observed in the Khari river channel, north of Bhuj	129
Fig 5.13 Morphological map of the south flowing rivers showing intensive ravine erosion	130
Fig 5.14a Longitudinal profiles for different north flowing rivers	133
Fig 5.14b Longitudinal profiles for different south flowing rivers	134
Fig. 5.15 Univariate plot showing Pseudo Hypsometric Integral values for different north and south flowing streams	136
Fig 5.16a Gradient index for different north flowing streams	137
Fig 5.16b Gradient index of different south flowing streams	138

Fig 5.17 Sinuosity fractal dimensions for different rivers studied within Kachchh Mainland	140
Fig 5.18 Drainage pattern on individual fault blocks studied	141
Fig 5.19 Line drawing showing the methodology used for calculating different parameters (after Talling et al, 1996)	143
Fig 5.20 Univariate plot showing the Drainage spacing ratio for different fault blocks studied	144
Fig 5.21a Plot showing the relationship between the Mean spacing and Mean outlet spacing, b) Plot showing the relationship between Mean topographic half width and Mean outlet spacing	145
Fig 5.22a Drainage basins of some of the north flowing streams	146
Fig 5.22b Drainage basins of some of the south flowing streams	146
Fig 5.23 Univariate plot showing the Drainage basin elongation ratio for different north and south flowing rivers, note that the ratio for south flowing rivers is in between 0.1 and 0.35 indicative of active influence of deformational movements on these drainage basins	147
Fig 5.24 Univariate plot showing the valley floor to valley height ratios indicating the general shape of the valleys (i.e. U shape or V shape), note that all the values are below 1 indicative of V shape valleys	148
Fig 5.25 Mountain front characteristics of Habo and Kas Hills	151
Fig 5.26 Figure showing the calculated parameters for the two subareas along the Kachchh Mainland Fault	152
Fig 5.27 Mountain front characteristics along Katrol Hill Zone	153
Fig 5.28 Mountain front sinuosity of 62 Mountain fronts in two sub areas along the Katrol Hill Zone	154
Fig 5. 29a Figure showing the drainage along the Kachchh Mainland Fault, b) the lineaments along that influence the drainage of the area	156
Fig 5.30 Figure showing the general morphology of alluvial and colluvial fans along the Kachchh Mainland Fault and Katrol Hill Fault	158
Fig 5.31 Morphology of Kaswali fan showing the drainage configuration of Kaswali river and the sites studied along the exposed succession of the fan	160
Fig 5.32 Figure showing morphology of Kaila fan alongwith the drainage basin configuration of Kaila river and sites studied along the exposed alluvial succession along the fan	162
Fig 5.33 Sedimentary successions studied at various sites along the Kaswali and Kaila fans	166

Chapter 6

Fig 6.1 The worldwide data showing farthest sites (from epicenter) at which the liquefaction took place. Y-axis shows the magnitude of the earthquake at which the liquefaction effects are seen. It is seen that the liquefaction becomes quite common at the magnitudes of > 5 (after Obermeir, 1996).	169
Fig 6.2 Seismic zones of India (after Jai Krishna, 1992)	171
Fig 6.3 Location map showing the sites at which different seismically induced deformational structures were observed as well as the trench sites observed in Great Rann-Banni region	173
Fig 6.4 Deformed succession of recent sediments near Dudhai	174
Fig 6.5 Small scale seismogenic slump folding and faulting in Mesozoic	175

sandstone succession near Bhuj	
Fig 6.6 Small scale folding in Tertiary rocks near Lodai (north of Bhuj)	176
Fig 6.7 Photograph showing sand dyke and Ball and Pillow structure in Bhuj sandstone near Mandvi	176
Fig 6.8 Small scale folding in the recent sediments of Great Rann-Banni area. The Photograph is of trench site 3 near Ludiya (3 km south of Khavda)	180
Fig 6.9 Sand dyke observed in one of the trench sites near Ludiya (also refer Fig 6.10)	183
Fig 6.10 Sand dyke from trench site 5 near Ludiya. Note the disruption of the overlying confining layer of clayey sediments and folding of the caly-silt beds due to the shear stresses produced by the propagating seismic wave.	184
Fig 6.11 Line drawing from a photograph showing well developed flame structure observed in trench site 2 near Bhirandiala, about 55 km north of Bhuj.	185
Fig 6.12 Line drawing of a well-developed slump and a wedge along slightly inclined faults observed in trench site 6 near Ludiya	187
Fig 6.13 Formation of a slump and a wedge along slightly inclined faults	188
Fig 6.14 Well-developed craters along small sub-parallel faults	189
Fig 6.15 A closeup view of well-developed craters observed in trench site 7 near Ludiya (Height of the trench is about 1.5m)	190
Fig 6.16 Micro-faulting of young sediments due to seismic trigger observed at trench site 8 near Ludiya	191
Fig 6.17 Temporal distribution of earthquakes in Kachchh region	193
Fig 6.18 Line drawing showing the development of normal fault in conjunction with the major reverse fault (drawn from Stewart and Hancock, 1990)	198
Fig 6.19 Line drawing showing the general deformation model of 1819 AllahBund earthquake	200
Fig 6.20 Map showing the earthquake distribution through out the Kachchh region	203
Fig 6.21 Map showing the major active faults of Kachchh region (modified after, Biswas and Deshpande, 1970)	203
Fig 6.22 Map showing the seismoactive lines throughout the Kachchh region (the base map of faults is taken from, Biswas and Deshpande, 1970)	209
Fig 6.23 Map showing four major seismic zones deduced from the population density of earthquakes (the base map of faults is taken from, Biswas and Deshpande, 1970)	213
Fig 6.24 Plot showing the G-R relationship for the frequency of earthquakes in Kachchh region	216

Chapter 7

Fig 7.1 Earthquakes felt in different major talukas in the last 200 years (based on the data of Kachchh gazetteer (1971) and Malik et al, (1999)	232
--	-----