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CHAPTER 1

INTRODUCTION

THE RATIONALE

Active tectonics is the prime factor governing the landscape evolution in seismically active areas. Characterization of geomorphic features in such areas is vital for estimating the influence of tectonic movements along faults in recent geologic past (Garcia et al. 2003). However, the landscape response to tectonic movements depends on the nature of uplift that can range from block uplift to tilting due to activity along bounding faults. Moreover, the nature of faults determines the style of structural and landscape deformation occurring in a region. Documenting the geomorphic indicators of active tectonics help in understanding current seismic activity in a neotectonic perspective. Generating geological data along the various active faults to understand their evolutionary history in the recent past is extremely important in view of the renewed conscious and concentrated efforts for evaluating the seismic hazard and mitigation in India (Chadha, 2010)

There is disagreement as to how far back in time ‘geologically recent’ is, with the common meaning being that neotectonics is the youngest, not yet finished stage in Earth tectonics. A general agreement has been emerging that the actual time frame may be individual for each geological environment and it must be set back in time sufficiently far to fully understand the current tectonic activity. Keeping in view of the fact, that the area of present study is located in Kachchh region, an area well known for recurrent seismic activity, it is imperative that the tectonic history of various faults is known for atleast the Quaternary period. In the present study, therefore, the tectonic activity that has occurred during the Quaternary period is classified as neotectonics. This meaning is implied at all places in the thesis wherever the term neotectonics is used.

The Kachchh basin is a E-W trending palaeo-rift graben that is currently undergoing active coseismic deformation as evidenced by the large scale changes in the landscape caused by large magnitude earthquakes in recent times as exemplified by the 1819 Allahbund earthquake and the 2001 Bhuj earthquake (Oldham, 1926; Bilham, 1998; Mandal and Chadha, 2008). The sedimentary sequence in the basin is approximately 4000 m thick, ranging from Lower Jurassic to Holocene with intervening Upper Cretaceous–Palaeocene basaltic flows of the Deccan Traps (Biswas, 1987). The Kachchh basin was
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formed during the middle Jurassic whose subsequent rifting phase in extensional regime continued up to late Cretaceous followed by inversion phase of the Cenozoic have left a profound influence on the landscape.

Presently, the intrabasinal landscape of the Kachchh basin is characterised by major fault bound uplifts which includes the Island Belt Uplift, South Wagad Uplift, Desalpar uplift and the Kachchh Mainland Uplift (Fig. 1.1). These uplifts have prominent geomorphological expression and are bounded by the Island Belt (IBF), South Wagad Fault (SWF), Gedi Fault (GF) and the Kachchh Mainland Fault (KMF) respectively. The tectonic evolution of Kachchh Basin is primarily controlled by movements along three principal sub-parallel faults, namely, Island Belt Fault (IBF), South Wagad Fault system (SWF) and Kachchh Mainland Fault (KMF). The uplifted blocks expose Mesozoic rocks deposited in the rift phase of the basin until late Cretaceous with a pronounced flexure zone comprising asymmetrical domes and anticlines of various shapes and sizes along the generally E-W trending faults bounding the uplifts. In-between these fault bound uplands, the depressions or plains were formed which are occupied by Neogene sediments with thin Quaternary sediment cover.

![Figure 1.1 Map of Kachchh basin showing the general geomorphic configuration and various uplift bounding faults (based on Biswas, 1987). The boxed area (continuous line) shows the extent of the presently active Kachchh Seismic Zone as delineated by Mandal and Chadha (2008). Smaller boxes (dashed line) indicate the faults zones and area covered in the present study. A- KMF zone, B- SWF zone, C-Samakhiali-Lakadia plain, D-GF zone, E-IBF zone. (Inset-Location map).](image-url)
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The Quaternary deformation in Kachchh basin is generally associated with the Indo-Eurasia collision in the north and the push from the spreading Mid-oceanic Ridge in the south (Thakur and Wesnousky, 2002). However, the Quaternary tectonic activity along the various faults has largely been a much neglected aspect in spite of the high seismic risk. The data available on this aspect is not commensurate with the amount and intense seismic activity witnessed in the Kachchh basin during historic times. This may be partially due to its vastness and remoteness and may be also because of the current political barriers blocking access in some regions. Though, a great deal of information on the pre-Quaternary stratigraphic and tectonic evolution of the basin is available, there are several major issues uninvestigated that can help to reconstruct the tectonic evolution during the Quaternary. Important questions that are unanswered concern the crustal controls on the distribution and kinematics of the various faults, rejuvenation of the fault zones, uplift mechanism, network of active faults including their connectivity, stress transfer and earthquake potential, and the role of tectonism versus climate in the geomorphological evolution of the region.

Despite an increased awareness of the potential for destructive earthquakes from faults within the Kachchh basin, very little information exists about the earthquake histories and recent kinematics of these faults. Specifically, the data available concerns to seismotectonic studies, majority of them carried out after the 2001 event, pre-Quaternary stratigraphic and tectonic evolution and few regional scale geomorphic studies. However, critical data of active fault parameters, recurrence intervals, dates and sizes of past events, slip rates, and kinematics for are non-existent. Furthermore, the exact nature and surficial location of many of these faults is not known. Such database is a primary requirement for constructing realistic probabilistic hazard maps for known active faults.

THE KACHCHH SEISMIC ZONE

On 26 January 2001, one of the deadliest intraplate earthquakes struck the western part of India, with conservative official estimate putting the number of human lives lost at 30,000 and the economic loss at US$ 10 Billion (Gupta et al. 2001; Rajendran et al. 2001; Thakur and Wesnousky, 2002). The epicentre of the earthquake was located at 23.326°N, 70.317°E, 15 km northwest of Bhachau and 60 km east of Bhuj (USGS). The earthquake was not surprising as the Kachchh region has experienced large earthquakes in the historical past (Thakur and Wesnousky, 2002). The May 1668 earthquake completely destroyed the town of Samaji (25°N, 68°E) (Burnes, 1835), and the 16 June 1819 Allahbund earthquake of magnitude > 8 in the Great Rann of Kachchh formed a mound
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90 km long and up to 9 m in height (Bilham, 1998). The Allahbund earthquake killed 1500 people in Bhuj and 500 in Ahmedabad (Oldham, 1883). On 19 June 1845, an earthquake shook the walls of the fort at Lakhpat where some lives were lost, and the sea rolled up the Kori creek, overflowing the area westward. During the 1845 earthquake from 19 to 25 June, 66 shocks were counted (Nelson, 1846). The 30 April 1864 earthquake was felt in Wagad, Ahmedabad and Surat (Wynne, 1872). Anjar earthquake of 21 July 1956 which killed about 150 people was the last major earthquake in this region before the 2001 event (Chung and Gao, 1995). Recurrent damaging earthquakes in Kachchh and other parts of India have necessitated the initiation of concrete steps to minimise the impact of seismic hazard (Chadha, 2010).

In the contemporary seismotectonic set up, all intrabasinal faults of the Kachchh basin are believed to be seismically active thereby characterizing the basin as the one with potentially multiple seismogenic sources (Rajendran et al. 2008). Details of the previous earthquakes are scanty, but the 2001 Bhuj earthquake (Mw 7.7) and the prolonged post-earthquake aftershock sequence have been studied in detail (Mandal and Chadha, 2008; Mandal, 2009). The area enclosed by the aftershock activity includes a vast area in the eastern part of the Kachchh basin and has been identified as the Kachchh Seismic Zone (Mandal and Chadha, 2008). The zone encloses several E-W trending fault zones viz, the eastern part of Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and the Island Belt Fault (IBF). These studies reveal progressive northward migration of seismic activity in the last decade which has generated several low to moderate magnitude earthquakes along the Gedi Fault and the Island Belt Fault (IBF) which lie to the north of the epicentral zone of the 2001 Bhuj earthquake (Mandal, 2008).

However, there are no studies available that document the neotectonic setting and history of these faults. Moreover, these faults are poorly constrained in terms of their precise location and shallow subsurface nature. This kind of data is helpful in understanding the neotectonic behaviour and stress accumulation along faults undergoing active coseismic deformation and also for carrying out future trench studies to delineate the palaeoseismic history. The present study is an attempt to delineate the geological parameters of the active faults of Kachchh Seismic Zone in a neotectonic perspective using field and GPR based studies.
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![Diagram of the Kachchh seismic zone with focal mechanisms](image)

**Figure 1.2** Spatial distribution of 470 focal mechanisms in the Kachchh seismic zone. Smaller beach ball represents solutions for the aftershocks of Mw 3.0-5.8. Medium size beach balls represent the focal mechanism solutions of the 7th March 2006 Mw 5.6 Gedi event and the 15th December 2007 Mw 4.5 ABF event. And, the largest beach ball marks the focal mechanism solution of the 2001 Mw 7.7 Bhuj main shock. Solid lines mark the known faults i.e. NPF, KMF, ABF, IBF, BF and KHF (after Mandal, 2009).

**SCOPE AND OBJECTIVES**

The present study was focused on establishing the location, extent and geometric/structural characteristics of the active faults in the Kachchh Seismic zone using extensive field and GPR based studies. The data generated on neotectonic setting, shallow subsurface fault characteristics, Quaternary stratigraphic development and geomorphic evidences of neotectonic activity are interpreted in conjunction with available seismotectonic studies. The study also attempts to explain based on neotectonic evolution and fault characteristics, the reasons for high and anomalous distribution of seismicity in the basin and vulnerability of the various faults to high magnitude earthquakes in a qualitative sense.

The present study is the first attempt at building up a comprehensive understanding of the active faults in the Kachchh Seismic Zone from a neotectonic
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perspective. The primary aim of the present study was to provide constraints on the location, shallow subsurface nature, neotectonic evolution and landscape shaping in the active fault zones of the Kachchh Seismic Zone. The study provides primary data base on geomorphologic, Quaternary stratigraphic, neotectonic evolution, GPR data constraining the precise location of active fault strand of the KMF, SWF, GF and IBF. Eastward lateral extension and propagation of the KMF up to the epicentral area of 2001 earthquake is established on the basis of unequivocal evidence from field and GPR studies. Active surface deformation going on in the Samakhiali-Lakadia plain as a response to KMF-SWF interaction has also been delineated. The data is used for qualitative characterisation of the active faults in terms of their potential to produce large magnitude earthquakes. The study also throws light on the causes of anomalously high and apparently unequal distribution of seismicity in the Kachchh basin as compared to the nearby tectonic terrains of the much fragmented western continental margin of the Indian plate. The data generated and presented in the subsequent chapters is intended to provide a basis for evolving seismic hazard models of the Kachchh basin.

The study was carried out to achieve the following objectives.

1. Delineate the relationship between the structural elements and the landscape configuration along the KMF, SWF, GF and IBF
2. Reconstruct Quaternary stratigraphy of the sediments occurring in the fault zones
3. Precise mapping of the near surface trace of the KMF, SWF, GF and determine their subsurface geometry and nature,
4. Reconstruct the neotectonic history and evolve a model of the Kachchh Seismic zone in contemporary seismotectonic setting.

STUDY AREA

Location

The present study is an attempt to provide neotectonic data on the active faults occurring within the Kachchh Seismic Zone. This zone roughly lies between 69° E and 71° E longitude and 23° and 24°N latitude (Fig.1.1). Intense aftershock activity, since the post-2001 Bhuj earthquake testify to the active nature of the various faults in the Kachchh Seismic Zone (Mandal and Chadha, 2008). The present study was focussed along the seismically active eastern part of the Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and the Island Belt Fault (IBF), all of which have prominent geomorphic expression as well. Detailed geomorphological studies were also
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carried out in the Samakhiali-Lakadia plain to characterise the active deformation caused by the KMF-SWF interaction.

Communication

The area within the Kachchh Seismic zone has a reasonably good network of metalled roads. The Ahmedabad-Kandla National Highway is the only national highway passing through the Kachchh district which connects it with other parts of the country. Some of the important state highways which connect Kachchh with the other districts are the Bhuj-Anjar-Gandhidham road, Bhuj-Mandvi Road and Bhuj-Desalpar-Roha-Naliya-Jakhau road. The small towns and villages are also well connected with a dense network of road. The Great Rann and Banni plain from a largely inaccessible terrain. However, Banni plain is criss-crossed by several tracks connecting various villages which are motorable in dry season. The rail link is also available through Lakadia-Bhachau and Gandhidham-Bhuj rail routes. Bhachau and Bhuj are the major railway stations from which other parts of the area can be accessed by roads. Bhuj airport is the only nearest working civilian airport.

Physiography

Physiographically, the study area can be divided into hilly terrain of Northern Hill Range, Wagad, and Island belt, gently undulating terrain of the Samakhiali-Lakadia plain, Banni plain and the Great Rann. The Northern Hill range marks the northern margin of the Mainland Kachchh which abuts against the Banni plain in the north. The straight north facing escarpment forming the northern margin of the range is the most conspicuous landscape feature of the area. This escarpment marks the geomorphic expression of the Kachchh Mainland Fault, the most significant geomorphological feature of the study area. The Northern Hill Range shows typical mountainous terrain with structurally controlled topography and deep valleys (Fig. 1.1). The Jhura hill forms the highest elevation which is located in the western most segment of the study area. The hill range gradually loses its elevation towards the east and disappears below the Samakhiali-Lakadia plain. The low level flat saline terrain of the Banni-Great Rann sub-basin represents the recently uplifted floor of a palaeo-gulf.

East of the Northern Hill Range lies the Wagad highland which is oval shaped rocky uplifted mass. Wagad is characterized by three main hill ranges named as- the Southern hill range, the Kanthkot hill range and the Northern hill range. Wagad hills are made up of Mesozoic rocks and occur as an isolated uplifted block surrounded by Tertiary rocks, Rann and alluvial sediments. A radial drainage is the characteristic of
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Wagad which is in the conformity of structural set up of the area. The drainages rises in the upland part of the Wagad and debouch in either Samakhiali-Lakadia plain or Ranns of Kachchh. Samakhiali-Lakadia plain lies south of the Wagad hill which is a flat surface comprises of thin cover of Quaternary sediments overlying the Tertiary rock. The low relief rocky terrain of the Desalpar Flexure zone lies to the north of Wagad.

The chain of islands comprising the Pachham, Khadir, Bela and Chorar islands together are termed as the Island belt. Pachham island forms the western most island which is characterised by hill range lying north and south margin of the island. The two hill range is separated by central valley which along which the major drainages of the region flows. On the contrary the Bela and Khadir island is characterized by the tilt block type of structure with a steep northern margin and a gentle back slope. Both the islands are characterized by southward flowing parallel drainage.

Drainage

The drainage of Kachchh provides an interesting example of a combination of lithologic and tectonic controls along with the influence of sea level fluctuations during Quaternary period. The drainage density of Kachchh is very high for a hyper arid region. The crest line of the Northern Hill forms the major drainage divide which have resulted in the north and south flowing drainages. The streams originating from the northern slopes of the Central highland, join the streams originated from the Northern hill range and pour their water into the Kaila, Pur, and Kaswali streams which, in turn, debouch into the Ranns. In general, the streams are ephemeral (seasonal) and carry water only during good monsoon. The Wagad region is characterized by the radial drainages reflecting a strong structure control. Adhoi river, Gupt river, Khari Vokra, Khari river forms the major river which rises from the southern margin of Wagad and drains the Samakhiali-Lakadia plain before joining the ranns and the Gulf of Kachchh. Overall, the drainages of the Wagad reflect a strong structural control. While the drainages of the Island belt is dominated by the parallel south flowing drainages developed over the gentle back slopes of the islands. Most of the streams incise through the compact Mesozoic rock forming deep valleys.

Climate

The Kachchh region is known for its arid to hyper-arid climatic conditions. The annual rainfall is about 250-400 mm/year, spread over the entire monsoon months of June to September. May marks the hottest month of the year where the day temperature reaches upto 48°C while January forms the coldest month of the year when the temperature may dip below 10°C. The range of wide temperature fluctuations is on
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account of the Tropic of Cancer passing through the Kachchh region. During summer, violent storms are frequently noticed in the area though they are of short duration. NW disturbances may result in prevailing of the cold wave which may result in lowering of temperature below the minimum level. Humidity generally remains high throughout the year which is more in the coastal parts.

Flora

The Kachchh region is very poor in vegetation because of scanty rainfall. The semi-arid desertic climate favours the growth of thorny, non-thorny trees and shrubs which includes Jal-salvador, Ganz grena, whereas thorny species includes Baval, Kher, Acacia, etc. Where in the Acasia Arabia (Gandobaval) covers major portion of the terrain. The coastline exhibits swamps vegetated with mangrove forests and grasses covering dunes and sand flats. The main varieties of flora found in the study area are - Avicennia officinalis (Tavar, Tarvariyan), Leptadenia spartium (Khip), Casuarina Equisetifolia (Saru), Halopyrum mucronatum (Dariyai Kansdo, Dariyai Kans), Melia azadirachta (Limbo), Acacia arabica (bav), Cassia auriculata (Aval), Sporobolus indicus (Velari charchar), Sueda maritima (Lano, Luno), Euphorbia tirucalli (Thor, Kharsani Thor, Dandali Thor) Leucoena glauca (Laso baval, Vilayati baval) Butea frondosa (Kesuda no jhad), Zizyphus jujuba (Bordi), Acacia jaquemonti (Tal bavari), Acacia leucophlaeae (Harmo baval), Tamarindus indicus (Arli), Sapindus emarginatus (Aritha), Cactus indicus (Hathlo thor), Ficus bengalensis (Vad), Eugenia jambolana (Jambu) etc. Wheat, Cotton, Bajara, Jowar, Mag and Math are common agricultural crops along with various fruits and vegetables.

Fauna

The vast land of Kachchh has long seashore and vast desertic condition which provide Kachchh an extraordinary variety of wild life attracting a large number of avifauna. The chief domestic animals found in the area are horses, camels, oxen, cow, buffaloes, sheep, goats and ass. The wild animals of the region include Panthera pardus (Panther), Chinkara (Gazella Gazella) (local name Chinkara) and the wild assse (Equus Onager Indicus) were found near the little rann of Kachchh. Neelgai or Blue Bull (Bojh), Wild Boar or Jungli Budhar (Sus Scrofa), Indian Wolf (Canis Lepus), Jackal or Shiyad (Canis Auresug), striped Hyena or Jharak (Hyena Hyonna), Desert Hare or Sasla (Lepus Nigricollis Ouchensis), Indian Fox (Vulpes Bengalensis), Mongoose (Herpestus Smithi), besides some jungli cats, desert cats, Pangolin, Indian Porcupine and long eared hedgehog are also found in Kachchh. The Indian Hare (Lepus Nigricollis) is commonly found in the
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open fields. The Caracal is the rarest animal found in Kachchh. Many kinds of reptiles including snakes are also found in Kachchh. Some of commonly found reptiles are Crocodile or Mugger, Monitor Lizard or Patla Gho, Kachchh Rock Gecho (Garodi), Desert Monitor Lizard, spiny-tailed lizard or Sanda (Uromastyx Hardwicki), flattened lizard or Khann, Starred Tortoise and frea water turtle (Lissemus Puctata) along with several varity of snakes both: Poisonous and Non-Poisonous. Black Krait, Black Cobra (Najatripudios), Russels Viper (Vipera Russeli), Saw Scaled Viper (Echlis Carinatus), Sea Snake (Hydrophis Spiralis) etc. are poisonous snakes, while Python (Python Molurus), Sand Boa (Eryx Conicus), Rat Snake (Pias Mucosus), Royal Snake (Zamenis Diadema) etc. are non-poisonous snakes. The resident and migratory birds are commonly found in Kachchh. The migratory birds are found plentiful during winter season in the organic rich zone of the coastal flats bordering the Gulf of Kachchh and the vast saline expanse of the Little Rann of Kachchh.

People and occupation

Kachchh district is inhabited by various groups and community. Around~ 80% of its population resides in the rural area so people are mainly dependent on agriculture and cattle rearing. The economy of the region is agro based and region is famous for its craft work. The construction of many big ports in the coastal parts of Kachchh has initiated the rapid industrialization between Gandhidham:-Mundra and Bhuj-Bhachau during the recent time, which has provided another window of opportunity for the people to earn their livelihood.

APPROACH AND METHODOLOGY

The Kachchh Seismic Zone is ideal for carrying out neotectonic studies. It is essential to employ a comprehensive approach involving geomorphic and stratigraphic data to enable reconstruction of a detailed geomorphic evolutionary history including the nature and timing of tectonic activity along active faults (Chamyat et al., 2002). The present study was carried along the active faults of the Kachchh Seismic Zone viz. the KMF, SWF, GF and IBF, which show significant imprints of neotectonic activities in recent past on the landscape and is affected by a prolonged aftershock sequence since the 2001 Bhuj earthquake. A comprehensive approach involving detailed field mapping of the landforms, DEM modelling and stratigraphic and shallow subsurface studies of the Kachchh Mainland Fault (KMF), South Wagad Fault (SWF) and Gedi Fault (GF) using
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GPR has been applied to reconstruct the geomorphic evolution of the study area. The detailed methodology employed for carrying out the present study is described below.

- Available published data on the stratigraphic, structural and seismotectonic aspects of the Kachchh region were critically studied and evaluated to understand the regional geological setting and possible influences of these on the geomorphic setup of the active fault zones.
- Regional scale geomorphic setup of the study area was delineated using Survey of India topographical maps and satellite images.
- Field mapping of various geomorphic features and landforms was carried out. The landforms of the study area were initially categorized into Quaternary and pre-Quaternary geomorphic features and were mapped separately before synthesising them to reconstruct a comprehensive neotectonic evolution of the study area.
- The DEM (Digital elevation models) of the study area were prepared with different resolutions to appreciate the role of various tectonogeomorphic features in landscape evolution.
- The exposed Quaternary sediments were studied with a view to understand the genetic aspects of the landforms and stratigraphic evolution. Both, the fluvial and colluvial sediments were investigated during the course of the study.
- Ground Penetrating Radar (GPR) was used for the precise mapping of the near surface trace of the KMF, SWF and GF and also for determining their nature in the shallow subsurface.
- Detailed remote sensing analysis was carried out for the flat terrain of the Samakhiali- Lakadia plain to delineate the geomorphic signatures of KMF-SWF interaction.
- The morphostratigraphic evolution of the fault zones was reconstructed based on detailed field criteria, field relationships of the various landforms and stratigraphic data. Major tectonic events responsible for the overall geomorphic evolution of the area were also identified.
- The field and GPR data were synthesised and compared to reconstruct the pattern and nature of neotectonic activity along the various fault zones. The results of the studies along the various fault zones were compiled to prepare a neotectonic model of the Kachchh Seismic Zone.