CHAPTER – 1

INTRODUCTION

THE RATIONALE

Seismic hazard is based on knowledge of past earthquakes, geology and tectonics and takes into account varied factors that may affect the strength of ground shaking at any given location. The hazard at remote areas experiencing frequent, large earthquakes is high with very low risk; while, densely populated areas experiencing moderate earthquake result into small hazard but high risk (Giardini et al., 1999). Earthquakes and also the secondary effects caused by them, such as tsunamis, landslides or rockfalls, avalanches, or liquefaction of soil cannot be prevented. A proper assessment of seismic hazard allows seismologists, geologists and engineers to develop meaningful guidelines and models allowing the society to develop appropriate measures and means to reduce the impact of earthquakes.

As a result of the northward movement of the Indian plate and due to transfer of stress in the interior part of the Indian subcontinent, earthquakes have been occurring in the Kachchh region of Gujarat since the historical times (Rajendran and Rajendran, 2001). The Kachchh region of Gujarat has already witnessed two massive damaging earthquakes—1819 Mw 7.8 Allah Bund earthquake and the 2001 Mw 7.7 Bhuj earthquake within the span of 182 years (Johnston and Kanter 1990; Rastogi, 2001). Additionally, the region has also experienced seven other $M \geq 6.0$ earthquakes (Quittmeyer and Jacob, 1979; Rastogi, 2001; 2004). In addition, 15 historic and recent earthquakes of M 5 – 6 have also been reported from the region (Rajendran and Rajendran, 2001). The severe shaking effects in the epicentral region of Bhuj earthquakes also produced widespread slumping and liquefaction features (Tuttle et al., 2001).

The intra-plate Kachchh paleo-rift basin, located at the western continental margin of the Indian plate (Figure 1.1), is characterized by multiple seismic sources (Biswas and Khattri, 2002). This is evidenced by the spread of historic and current seismic activity along the E-W trending intra-basin fault systems. Available fault plane solutions of high to low magnitude earthquakes suggest reverse dip slip with strike-slip component under compression (Singh et al., 2016). This is consistent with the ongoing inversion of the basin under NE directed compressive stresses in response to continued push of the Indian plate against the Eurasian plate along the Himalayan orogenic belt in the far north (Maurya et al., 2017a; Shaikh et al., 2020). Since the last high magnitude 2001 Bhuj earthquake (Mw 7.7) and the prolonged aftershock sequence, the eastern part of the Kachchh basin is identified as the Kachchh Seismic Zone (Mandal and Pandey, 2010) that encloses the Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and the Island Belt Fault (IBF) (Figure 1.1).

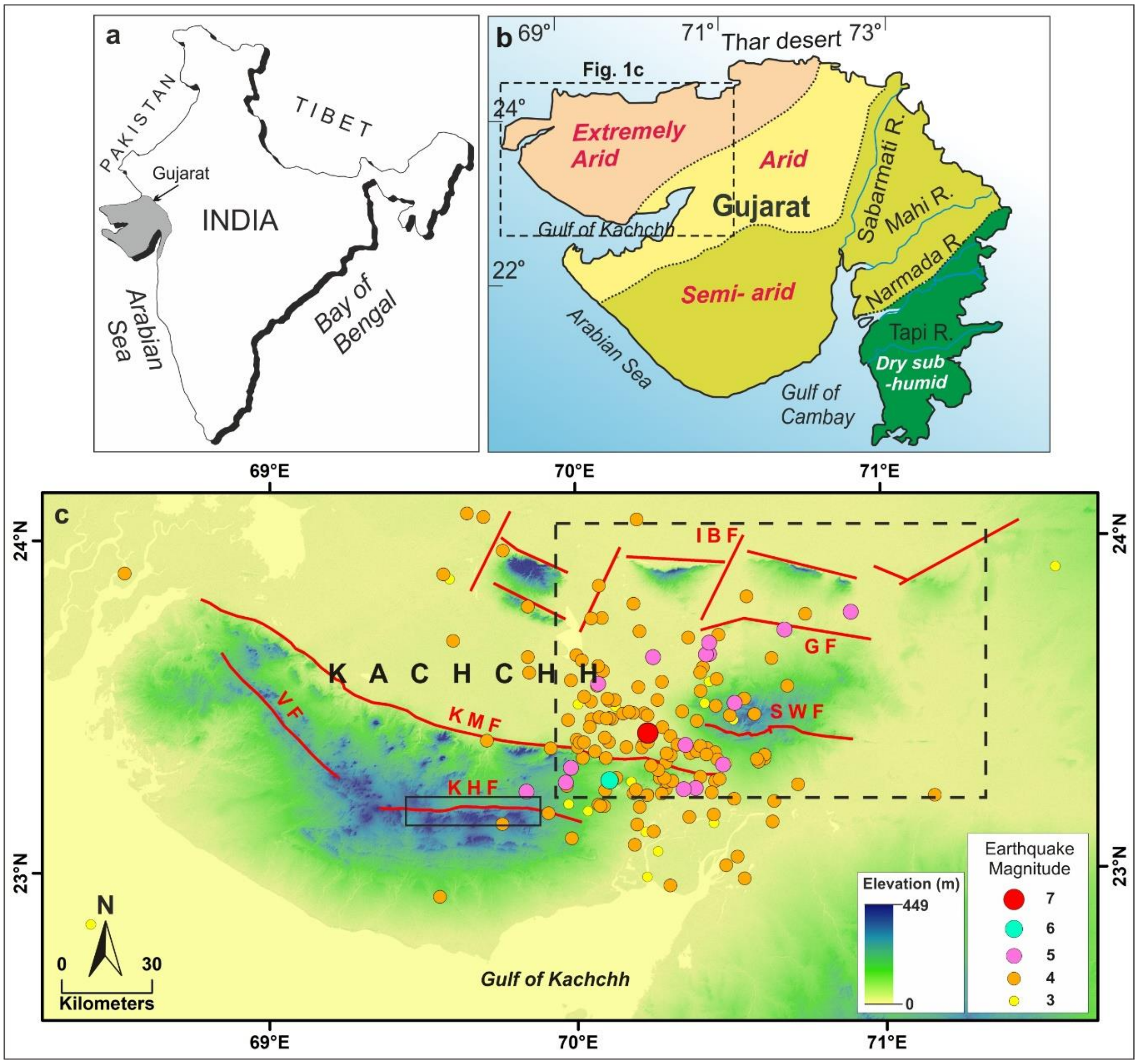

Figure 1.1 a. Location map. **b.** Map of Gujarat state showing climatic zones (source: imdpune.gov.in). Boxed area shows the area of Kachchh. **c.** DEM of Kachchh region showing major uplifts – Island Belt Fault (IBF), Gedi Fault (GF), South Wagad Fault (SWF), Kachchh Mainland Fault (KMF), Katrol Hill 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 present study along the Katrol Hill Fault (KHF).

Seismic activity in the Kachchh basin has received significant attention since the 2001 Bhuj earthquake (Mw 7.7), which occurred along the eastern fringe of the KMF (Bodin and Horton, 2004; Mandal et al., 2004; Rajendran et al., 2008). A large number of low to medium magnitude earthquake have been recorded that have occurred along the KMF, SWF, GF and IBF (Mandal and Pandey, 2010; Rastogi et al., 2013). This entire part of the eastern Kachchh is characterized by post-2001 moderate to low seismic activity is now recognized as the Kachchh Sesimic Zone (KSZ), which is currently being intensively studied and monitored (Mandal and Chadha, 2008; Mandal and Pandey, 2010; Vorobieva et al., 2014; Mandal, 2016; 2019). The eastern part of Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and Island Belt Fault (IBF) fall within the Kachchh Seismic Zone.

However, the KHF is shown to be located outside the Kachchh Seismic Zone (KSZ) (Mandal and Chadha, 2008), leading to a possibility of underestimation of seismic risk posed by the KHF. This is possibly because the KHF has remained seismically inactive in the post-2001 period and also that it does not show significant historical seismicity apart from very few low magnitude shocks (Malik et al., 1999). In such a scenario, it is likely that the KHF may be underestimated as a credible/potential seismic source in the region, which usually happens with faults that have longer periods of quiescence, for example, the 2008 Wenchuan earthquake along the Longmenshan Fault (Sun et al., 2019). This lack of geologic data pertaining to the active fault parameters in a region may result in an apparently low and incorrect characterization of seismic hazard in that region.

While KMF, SWF, GF and IBF have been shown to be neotectonically active (Chowksey et al., 2010; Maurya et al., 2013; 2017a, b), no evidence of surface faulting/rupture is reported along them. In contrast, three surface faulting events during Late Quaternary have been reported previously from the Khari river section located along the KHF (Patidar et al., 2008; Kundu et al., 2010). However, the lateral extension and other parameters of the Late Quaternary surface faulting are not known, which are necessary for precise estimation of seismic hazard in the region. The KHF also needs to be characterized in terms of the maximum possible/credible earthquake, which can occur in future, since it already shows evidence of surface faulting during Late Quaternary.

The recognition and analysis of earthquake induced effects, like surface ruptures, are very effective, both for identifying earthquake parameters and for assessing the vulnerability of the natural environment for seismic hazard evaluation (Esposito et al., 2000; Naik et al., 2020). Locating the primary fault trace, characterizing the rupture parameters such as surface rupture displacements, geological evidence of secondary faulting and subsurface geology are required to understand and mitigate the surface rupture hazard (Avar and Hudyma, 2019). Mapping of surface faulting also provides constraints on recurrence intervals and magnitudes and identifying features and aspects for additional study (Wheeler, 2006). A modern analogue of damage due to surface rupture is the 1999 Chi-Chi, Taiwan (Mw =7.6) earthquake, which caused a 90-km-long rupture at the surface and it was noted that damage to structures from surface ruptures was as high as 35–50% (Dong et al., 2019).

Identification, mapping and characterization of primary surface rupture traces is a standard practice to unravel the seismogenic characteristics of a fault (Wesnousky, 1986, 2008; Crone and Haller, 1991; Kanaori and Kawakami, 1996; Treiman et al., 2002; Huang et al., 2018; Huayong et al., 2019). Such studies have been attempted for historical as well as pre-historic earthquakes by Pavlides and Caputo (2004), Wesnousky (2008), Hao et al. (2009) and Trippetta et al. (2019). Study and mapping of historical surface ruptures, especially of those that occurred in the instrumental era is relatively straightforward. In contrast, the surface ruptures that occurred in the pre-historical time require application of diverse geological methods for their recognition and mapping. This is also true for faults that have long recurrence intervals or faults that do not have a known seismic history, for e.g., The Lavic Lake fault (USA) (Treiman et al., 2002). Erosional processes, poorly preserved fault scarps, burial under young sediments and post-depositional processes are some of the factors that can make the recognition and mapping of the surface ruptures challenging (Quigley et al., 2012). Surface rupture dimensions along active faults are crucial for estimating the size of paleo-earthquake events using empirical relationships (Slemmons, 1977; Wesnousky et al., 1984; Wells and Coppersmith, 1994; Trippetta et al., 2019).

The work by Wesnousky et al. (1983; 1984) and Wesnousky (1986) support the hypothesis that a complete knowledge of the geologic record of Quaternary fault offsets is sufficient to predict both the spatial and size distribution of earthquakes through time in a region characterized by shallow seismicity and active faulting. The active nature of KHF is already known (Patidar et al., 2007; 2008; Kundu et al., 2010; Maurya et al., 2016) and that the Kachchh rift basin along the KHF is characterized by apparent low crustal earthquakes and low-level seismicity (Mandal, 2016). However, the fast-spreading urban sprawl, especially of the Bhuj city, now overlapping the fault line and the fast-developing industrial corridor within the 5-10 kms zone along the fault line imply that the estimation of surface rupture hazard and its seimogenic potential is necessary. The present study is aimed at geological characterization of the KHF as a potential seismic source for improved future seismic hazard estimations and mitigation strategies in Kachchh region.

OBJECTIVES

1. Geological characterization of the Katrol Hill Fault (KHF) as a potential seismogenic source.
2. Estimate moment magnitude (M_w) of past surface faulting events along the KHF and its implication on earthquake hazard.

STUDY AREA

Location

The state of Gujarat on the western continental margin of India is divided into three different zones: Kachchh, Mainland Gujarat and Saurashtra. The zone of Kachchh forms the northern and the northwestern portion of Gujarat state and is the largest district of Gujarat State. The district possesses a vast sea coast with one major port, two intermediate ports and three minor ports situated on its coastline. The study area, the Katrol Hill Fault (KHF) is located in the central part of the Kachchh mainland (Figure 1.1). The area of present study is enclosed within 23°09'00" and 23°14'00" N latitudes and 69°23'00" and 69°55'00" E longitudes and covers parts of Bhuj, Anjar and Nakhatrana talukas of Kachchh district.

Physiography

The study area, located to the south of Bhuj city, is marked with the presence of east-west trending Katrol Hill Fault (KHF). KHF divides the region into two main physiographic units. Towards the north of KHF is the undulating rocky plain around Bhuj and towards the south lies the Katrol Hill Range (KHR), which corresponds to the flexure zone consisting of domes and anticlines, wherein the peak of Khatrod dome marks the highest elevation. The occurrence of faulting in the Quaternary sediments and incision of Quaternary miliolite terrace deposits in the Khari river along the KHF indicates seismically active nature of KHF. The Katrol Hill Range (KHR) is also dissected by several N-S, NNE-SSW and NNW-SSE trending igneous intrusive dikes and NNE-SSW, NNW-SSE trending transverse fault offsets.

Communication

Various road-rail-air and water routes link the Kachchh region well with the other regions. The state and national highways connect the Kachchh district with the other parts of the state and country. On rail network, the district is linked with Ahmedabad through broad gauge, while with Palanpur through meter gauge that gives connectivity to the other parts of the country. Bhuj and Kandla airports are the only two functioning civilian airports to reach Kachchh. All towns and major villages in and around the Bhuj district have post, telegraph and telephone facilities. From the Bhuj district, the Mandvi-Bhuj highway, and other metaled roads such as the Bharasar road, Mundra-Bhuj road, Tapkeshwari road led to the study area.

Drainage

In spite of the hyper-arid climate, there are numerous rivers in Kachchh district, some of these rivers flow into the Arabian Sea, while some feed the Gulf of Kachchh and Banni plain. These rivers are essentially ephemeral or intermittent (non-perennial) type of rivers owing to the hyper-arid climate of the region. The Katrol Hill Range located in the central part of rocky mainland acts as a major drainage divide, which is the controlling factor responsible for the development of most of the north- and south-flowing rivers. Arising from the northern flank of the Katrol Hill Range at altitudes of 187-348 m, the north-flowing rivers debouch into the Banni plains after crossing the rocky plains of Bhuj and the Northern Hill Range. The major north flowing rivers of the study area are Khari, Pat, Dharawa and Pur rivers. The south-flowing rivers such as Nagwanti, Phot, Rukmavati and Bhukhi rivers meet the Arabian sea. The drainages are regarded as experiencing the erosional phase, which is indicated by their incised channels.

Climate

The Kachchh region experiences hyper-arid type of climate as the region is characterized by short, irregular but high intensity rainfall pattern. The average annual rainfall of the entire region is approximately 340 mm. Most of the annual rainfall is received during the southwest monsoon season. Temperature shows seasonal variations from as low as 0° C during winter to as high as 48° C during summer; whereas the study area records 13° C as the lowest and ~40° C as the highest temperature during winter and summer, respectively. May is the hottest month of the year. High humidity is found along the coastal tracts of Kachchh, situated to the south of the study area.

Flora

Nearly 700 species of Angiosperm plants have been identified in the Kachchh region, which comprise of 95 families and 367 genera (Rao, 1970). Thorny shrub vegetation constitutes most part of the forest cover found in the study area. Medicinal plant species such as *Phoenix sylvestris* Roxb., *Grewia* tenax Fiori, *Adhatoda vasica* Nees, *Asparagus racemosus* Willd. var. *javanica* Baker, *Barleria prionitis* L., *Datura metel* L., *Helicferesi sora* L., *Withania somnifera* Dunal, *Peganum harmala* L., *Eclipta pros/rata* L., *Oommiphora wightii* (Arn.) *Bhandari, Psoralea corylifolia* L., *Solanum surattense* Burm. f., *Tribulus terrestris* L., *Oxystelma esculentum* R. Br., *Periploca aphylla* Decne are found. Some important tannin-yielding plant species are *Cassia occidentalis* L., *O. auriculata* L. and *Acacia chundra* Willd. Gum yielding plant species such as *Acacia nilotica* (L.) Del. sub sp. *indica* (Benth,) Brenan, *A. farnesiana* Willd. and *Oommiphora wightii* (Arn.) and oil yielding plants species such as *Ricinus communis* (seeds), *Mimusops elengi* L. (seeds), *Cymbopogon martinii* Stapf. (Rosha Oil from leaves) and *Vetiveria zizanioiduz* Stapf. (roots) are also found in Kachchh.

Fauna

A large number of faunal species have been reported from Kachchh. Some common domestic animals such as hoses, camels, sheep, goats, cows and buffaloes are reared by the people. Among mammalian species, Long-eared Hedgehog (*Hemiechinus auritus*), Indian wolf (*Canis lupus pallipses*), desert fox (Vulpes vulpes pusilla), Chinkara (*Gazelle gazelle*), desert cat (*Felis silvestris*), Indian porcupine (*Hystrix indica*), Indian ratle (*Mellivora capensis*), caracal (*Felis caracal*) and striped hyena (Hyena hyena) are known to exist in and around the study area. Rare and endangered bird species includes Hobara Bustered (Chlamydotis undulate), Lesser Flamingo (*Phoenicopterus minor*). Herpetofaunal species like Indian flapshell turtle (*Lissemys punctata*), spiny tailed lizards (*Uromastyx hardwickii*), saw-scaled viper (*Echis carrinatus*), black cobra (*Naja oxina*) are very common in Kachchh. Kachchh is also famous for the last remaining population of Wild Ass (*Equus hemionus khur*) in the Little Rann to the east of the study area.

People and occupation

Kachchh district is inhabited by various groups and communities such as nomadic, semi nomadic and artisan groups. The significant industries in Kachchh include engineering, power, steel pipes, cement, handicrafts. Emerging industry sectors include construction, chemicals, ceramics and textiles. agriculture and animal husbandry are the chief economic activities in the district. Agriculture is an important revenue generator of the district. Livestock breeding is a very important agriculture related activity for the people living in and around the study area. Animal husbandry is the second largest employment providing activity in the study area and is the main source of livelihood for shepherds and many nomadic tribes in Kachchh. The study area consists of the reserves of limestone and bentonite, which serve as raw materials to various mineral based companies located in different parts of Kachchh district. Kachchh is one of the most prolific regions in India in the area of textile art. The Bhujodi village, located in the study area is famous for different hand-crafted items such as traditional clothes and jewelry. Presently, the Bhuj-Bhachau-Anjar corridor comprises of several large industries that have come up in the post-2001 Bhuj earthquake time.

APPROACH AND METHODOLOGY

A largely rocky landscape coupled with a lack of good complete sections, except the Khari river section, meant that the tracing of Late Quaternary surface faulting along KHF could not be done using routine field mapping alone. In view of this, the approach and methodology applied in the present study were largely governed by the area-specific conditions. An interdisciplinary strategy that used field mapping, shallow geophysical studies using GPR, microscopic studies using optical microscopy and Scanning Electron microscopy (SEM) was followed. Detailed field investigations were carried out to map the Quaternary deposits in the area and samples were collected from the Quaternary deposits found in the KHF zone for analyses under the optical microscopy and Scanning Electron Microscopy (SEM) to examine the presence of microtextures related to coseismic faulting processes and to precisely locate the surface rupture trace of the KHF. The field investigation was also accompanied by shallow subsurface geophysical surveys with Ground Penetrating Radar (GPR) and data was acquired in the form of two-dimensional (2D) profiles along transects overlain by Late Quaternary deposits concealing the surface trace of KHF. The parameters such as surface rupture length, displacement and slip rate derived from the above-mentioned analyses were used to estimate the magnitude of paleo-earthquake along the KHF using various empirical relationships. The presence of buried paleo-valley and the wind gap, which resulting due to surface faulting along KHF in the Gunawari and Gangeshwar river basins was also established using the GPR studies assisted by geomorphic cross-sections, longitudinal river profiles, morphometric parameters and Chi (χ) analysis.

The methodology followed in the present work is discussed in brief as follows.

- Identification and mapping of various tectonic and geomorphic landforms, active faults based on satellite data, drainage patterns and preparation of base maps by satellite imagery interpretation.
- Detailed geological and geomorphic mapping of Late Quaternary tectonic landforms and examining outcrops of Quaternary sediments lying precisely over the KHF. Drainage lines and physiographic data were digitized from Survey of India topographical maps (41E/8, 41E/12 and 41E/16) on 1:50,000 scale.
- Field mapping was supplemented by shallow sub-surface geophysical studies using GPR and Quaternary sediment sampling for microscopic studies including petrography and SEM.
- GPR data processing using RADAN software and sample preparation in laboratory for analyses using optical microscope and high- resolution SEM.
- Estimation of the surface rupture length, displacement and slip-rate of surface faulting events along KHF by integrating field evidences along with shallow subsurface GPR data and microscopic data obtained from optical microscopy and SEM.
- The three estimated parameters of Late Quaternary surface faulting such as surface rupture length, displacement and slip rates were used to estimate the magnitude (Mw) of paleo-earthquakes by using different empirical equations.
- Calculation of morphometric parameters and Chi (χ) analysis to decipher the process of drainage reorganization in Gunawari and Gangeshwar river basins.
- The data generated in the field as well as from multidisciplinary studies in the laboratory were synthesised and critically evaluated to delineate the implications of surface rupture hazard in Kachchh basin.