

CHAPTER 1

INTRODUCTION

THE RATIONALE

Uplift patterns and topography have been used successfully to infer the geometry of the responsible interacting faults, even in complex structural settings with different fault geometries and sense of slip (e.g., Taboada et al., 1993; Meigs et al., 2008; Landgraf et al., 2009, 2013). However, faults in tectonically active regions reflect both present and past tectonic conditions which means that they may not simply reflect fault motion driven by the current ambient crustal stresses (Landgraf et al., 2013). Though tectonic landforms are normally used to characterize tectonic activity, inherited elements make assessments of modern stress conditions and tectonic displacements difficult (Landgraf et al., 2013). Several studies have noted that reactivation of inherited structures under changing boundary conditions can have important impacts on landscape response (Landgraf et al., 2013). The intriguing possibility of relating inherited landscape remnants to changing tectonic conditions constitutes the basis for investigating simple and composite tectonic landscapes where inherited topography generated under different (earlier) tectonic conditions might exist (Landgraf et al., 2013).

Faulting is a process that involves several different physical mechanisms, which may differ depending upon the rock type and the tectonic setting (Pollard and Fletcher 2005). Fault interaction is also observed at a range of spatial scales involving an alternation of slip rates on neighbouring fault systems (Rockwell et al. 2000; Peltzer et al. 2001; Pollitz and Sacks 2002; Friedrich et al. 2003; Bennett et al. 2004; Niemi et al. 2004; Dolan et al. 2007; Landgraf et al., 2009, 2013). Faulting scenarios may become even more complex if a re-orientation of the tectonic stress field triggers the reactivation of dip-slip faults as obliquely slipping or pure strike-slip faults (Strecker et al. 1990). Fault scaling laws then suggest a systematic relationship between the amount and along-strike distribution of displacement for a given fault length, such that over time, the topography of a landform (mountain, ridge, basin) might reflect the slip distribution along the responsible faults (e.g., Scholz, 1982; Cowie et al., 1993; Dawers et al., 1993; Dawers and Anders, 1995; Ellis and Dunlap, 1988), and systematic changes of

topography along strike can be expected (e.g., Taboada et al., 1993; Hetzel et al., 2004; Densmore et al., 2005). These relationships underscore the different levels in the complexity of fault development and the necessity to identify and evaluate spatiotemporal fault behaviour. It is important to consider fault growth and interaction when assessing tectonic landforms, particularly if such landforms are being used to characterize the degree of tectonic activity of a region (e.g., Stein et al., 1997; Cooke and Kameda, 2002; Anderson et al., 2003; Lin and Stein, 2004).

Fault linkage and subsequent interaction on the field-scale has been primarily studied in detail in extensional settings (e.g. Dawers et al. 1993; Cowie et al. 1993, 2000; Armijo et al. 1996; Densmore et al. 2003), and from the perspective of strike-slip partitioning and weak versus strong fault behaviour, particularly along the San Andreas Fault (e.g. Teyssier and Tikoff 1998; King et al. 2005), where fault-normal crustal compression parallel to the strike-slip fault is observed. However, on a regional scale, the problem of fault interaction and the effects of a changed tectonic stress field on the kinematic evolution of faults in areas governed by shortening seems is not well understood.

Tectonic stresses are mostly responsible for the deformation of the Earth's lithosphere (Zoback et al., 1989; Goswami et al., 2020; Lahiri et al., 2020). Discrete intra-continental, passive rift systems are marked by extension localized in narrow zones (< 100 km wide) e.g., the East African Rift, Baikal rift zone, West Antarctic rift, Rhine graben and Rio Grande rift (Ruppel, 1995). Passive rifting is initiated with lithospheric thinning in response to the far-field extensional stresses that may be generated by plate boundary forces (Ruppel, 1995). Specifically, positive basin inversion tectonics involves reactivation of normal faults, formed during earlier crustal extension, and subsequently as reverse faults during compression (Williams et al., 1989; Schlische, 1995; Sibson, 1995). Examples include the Missouri basin in Morocco (Beauchamp et al., 1996), Rio Grande rift of central New Mexico (Ricketts et al., 2015), Kachchh rift basin of western India (Chung and Gao, 1995; Biswas, 2005; Maurya et al., 2016), Sierras Pampeanas of Córdoba in Argentina (Martino et al., 2016) and Faeroe-Shetland Basin in northern offshore part of United Kingdom (Davies et al., 2004). Contraction during positive inversion is either oblique or co-axial with the earlier extension direction (Wessex and Weald Basins of southern England: Stoneley, 1982; Simpson et al., 1989; Butler and Pullan, 1990; Taranaki Basin in New Zealand: King and Thrasher, 1992; Sibson, 1995). Only a few set of pre-existing normal faults or

individual segments of normal fault strands reactivate during inversion demonstrating selective nature of fault reactivation (Sibson, 1995).

Compressive stress regime related to strike-slip and collision/subduction would not exclusively result in reverse faulting and/or inversion in an extensional setting. Reverse faults at the continental rift margins are also produced in response to compressive stress regime associated with the far-field ridge-push forces along seafloor spreading margins. The Fundy rift basin (Canada; Withjack et al., 1995) is an example. Besides, isostatic flexure-induced contraction in uplifted footwall can also result in reverse faulting (e.g., the Rio Grande rift margin: Lewis and Baldrige, 1994).

The Kachchh rift basin (KRB) at the western continental margin of India is well for its neotectonically active nature and recurring high magnitude earthquakes (Biswas and Khattri, 2002; Maurya et al., 2017). However, the kinematic relationship and interaction between adjacent faults is not investigated till now. The KRB is well-suited for investigating the modern topography, fault geometry and constraints on the tectonic history to test how tectonic forcing may have influenced landscape evolution (Fig. 1.1).

Understanding the nature of possible interaction between these faults is crucial for the evaluation of regional tectonic activity and the overall assessment of the evolution of fault systems that account for major share of the shortening during the Cenozoic. Being a region of active tectonics, geomorphic analysis can be usefully combined with structural mapping to elucidate the geometry, kinematics and timing of motion on active structures. Structural mapping permits identification of principal faults, while geomorphic analysis provides a more complete understanding of the locations and displacements along faults.

In the present study, the style of deformation observed along the different fault systems of the western KRB is characterized through field observations to constrain the distribution of deformation. The data utilized in the study comprises fault kinematics, structural data and geomorphic observations which indicates that the deformation pattern has changed over time. Using these data, history of deformation is reconstructed to infer how the deformation may be related to the changing stress field in this area. The study is basically an attempt to understand the kinematic evolution of the fault systems and its linkage to the landscape development. A better knowledge of temporal aspects of faulting therefore is relevant for the evaluation of seismotectonic segments and associated landscape development that span the Quaternary time and beyond.

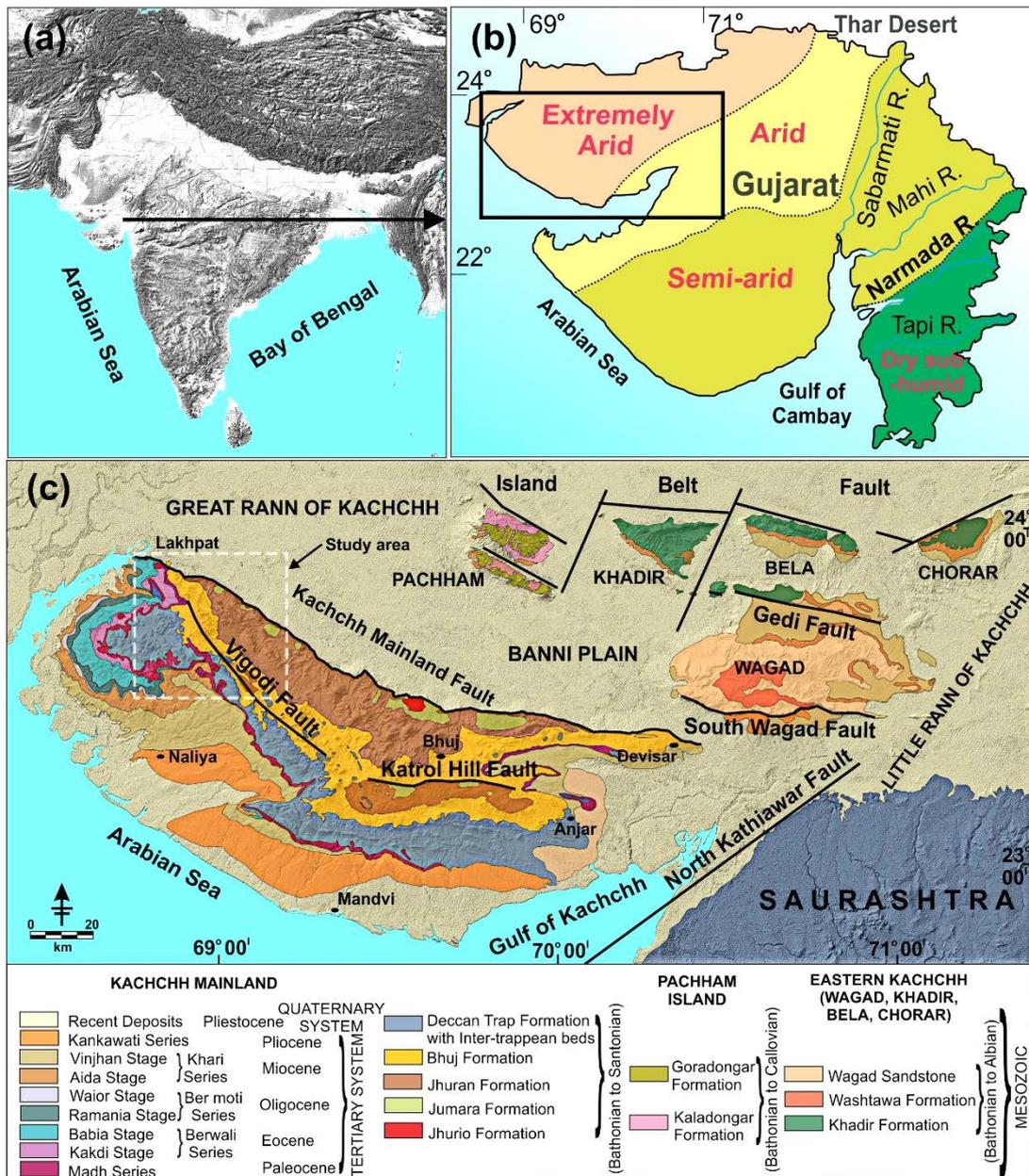


Fig. 1.1. (a) Map of India showing the location of Gujarat state. (b) Map of Gujarat state showing the climatic zones. The boxed area shows the Kachchh basin. Note that the Kachchh basin falls in the hyper-arid climatic belt. (c) Geological map of the Kachchh basin superimposed over Digital Elevation Model (DEM). Geological details are after Biswas, (1993). Figs. (a), (b) and (c) are modified after Shaikh et al. (2019). Box shows the study area.

Studies on the tectonic geomorphology of fault zones have been found useful for delineating fault characteristics and neotectonic evolution (Patidar et al., 2007; Maurya et al., 2008; Sagripanti, 2015; Zhang et al., 2017). A fundamental aim of the tectono-geomorphic studies is to establish the link between tectonic forces and

geomorphological processes in shaping the landscape of the areas that have undergone significant deformation during the Cenozoic Era (Burbank et al., 1996; Van der beek et al., 2001; Schoorl and Veldkamp, 2003; Bishop, 2007). In this sense, tectonic geomorphology provides critical data on understanding long-term deformation based on identification and mapping of geomorphic landforms to provide the sequence of morphostratigraphic evolution, which can serve as a reference frame for further seismotectonic and paleoseismic studies.

The present study was carried out in a geologically significant and uninvestigated western part of the seismically active Kachchh Mainland Fault (KMF), which is the largest intra-basinal fault in KRB (Fig. 1.1). It is also considered as the one with highest seismogenic potential in the KRB, exemplified by the occurrence of devastating 2001 Bhuj earthquake (Biswas, 2005). The KMF is characterized by a flexurally folded fault controlled hill range, the Northern Hill Range Fault Zone (NHRFZ) in the southern upthrown block and a Quaternary basin in the northern downthrown block (Biswas, 1987). The Jumara and Jara domes forming part of the NHRFZ, is geomorphologically significant as it comprises the spectacular Jaramara scarp that is parallel but considerably higher than the KMF scarp. The various mega-scale geomorphological units have been compared and the probable sequence of Cenozoic tectonic movements have been reconstructed that led to the development of the present day landscape.

SCOPE AND OBJECTIVES

The landscape of the basin is strongly controlled by E-W trending tectonic fabric as reflected by the trend of uplift bounding faults (Fig. 1.1). All major faults in the KRB qualify to be categorized as active as indicated by the available data and distribution of earthquakes that have occurred during a historic time in the basin (Biswas, 2005). Due to lack of neotectonic history of the various faults, it has been presumed that the tectonic loading is shared by the array of potentially active faults in complex ways both spatially and temporally (Biswas and Khattri, 2002; Mandal, 2009). Based on the moderate and low magnitude earthquakes, a large volume of seismotectonic data has been generated since the 2001 Bhuj earthquake (Mandal, 2009; Maurya et al., 2017).

Few studies have shown the influence of Late Quaternary tectonic activity on the geomorphology of the fault zones mainly Katrol Hill Fault (KHF) (Patidar et al.,

2007, 2008), eastern part of KMF (Chowksey et al., 2011a, 2011b), Gedi Fault (GF) (Maurya et al., 2013), South Wagad Fault (SWF) (Maurya et al., 2017b), Island Beld Fault (IBF) (Chowksey et al., 2010, 2016) and Allah Bund Fault (ABF) (Padmalal et al., 2019). However, no attempt has been made to link the long-term landscape evolution of the fault zones, especially the narrow flexure zones adjacent to the faults. An attempt has been made to understand the long-term landscape evolution in response to uplift induced structurally controlled erosion due to differential movement along faults.

A geologically significant part of the (i) seismically active ~W-striking KMF, which is the largest intra-basinal and uplift-bounding fault and, (ii) intra-uplift NW- to NNW-striking Vigodi-Gugriana-Khirasra-Netra Fault System (VGKNFS) have been investigated. The present study focuses on imaging and detecting the surface as well as sub-seismic geometry of the western part of the seismically active W-/NW-/NNW-striking KMF and NW- to NNW-striking VGKNFS employing structural studies in field and GPR surveys (Fig. 1.1). Because of the patchy and isolated rock exposures, presence of neotectonic/geomorphic evidence, the study area was selected for GPR-based work. The GPR cross-sections were evaluated to determine whether the impact of any Quaternary movements along the buried faults could be detected by displacement and/or folding of the near-surface sediments. Cross-sections generated from GPR surveys by previous workers in the KRB revealed only the major blind active faults. In the present work, along with the detection of the major blind fault, associated deformational structures are imaged, which are developed in the fault damage zone e.g., colluvial wedge, off-fault folding, subsidiary antithetic and synthetic fault strands. An attempt is also made to infer the subsurface fault zone stratigraphy. Conventional geological and paleoseismological studies have not detected these structures. With the aid of GPR images, a multitude of secondary active faults distributed in the KMF deformation zone have been delineated in a non-invasive manner and made their integrated correlation with the exposed surficial evidence. The study has implications for understanding neotectonic and seismic hazard estimation in the western part of the KRB.

Also, the aim of the present study is to understand the temporal and spatial evolution of the acting stress field. The existence of two end-member phases of deformation that prevailed since the Mesozoic from extension to compression is derived. The kinematic analysis of brittle structures is performed that provides insights

to relate the evolution of faults with the prevalent regional tectonic stress conditions that (re)activated the faults. Inversion of fault-slip data gives the orientation of principal stress axes. Knowledge of the present-day stress field is critical for seismic hazard estimation and mitigation. Also, it is equally important to understand the paleostress field operating at the time of faulting to reconstruct the tectonic evolution of faults in the KRB. The state of tectonic stress can be inferred from the geological and geophysical data e.g., inversion of earthquake Focal Mechanism Solution (FMS), borehole breakouts (BO), drilling-induced fractures, in-situ stress measurements (overcoring and hydraulic fracturing), geological indicators (fault-slip data, volcanic vent alignments) (Zoback, 1992). These provide an accurate estimate of the prevalent paleostress as well as present-day stress conditions.

No attempt has been made so far to reconstruct the paleostress state using geological indicators and to understand the kinematics and brittle tectonics of the KRB. Notably, Vanik et al. (2018) has carried out paleostress analysis using geological indicators along the E striking Katar fault from SW Saurashtra region of Gujarat state, which is ~370 km S of the study area and may not have direct implications.

The present research was carried out to achieve the objectives listed below:

1. Delineate structural characteristics and paleostress patterns in the western part of the Kachchh Mainland Fault (KMF) and associated Vigodi-Gugriana-Khirasra-Netra Fault System (VGKNFS).
2. Reconstruction of Late Cenozoic tectonic evolution and consequent landscape evolution of the western part of the Kachchh paleorift basin (KRB).

STUDY AREA

Location

The seismically active E-W striking KRB is located in the state of Gujarat on the western continental margin of India (Biswas and Khattri, 2002; Maurya et al., 2016) (Fig. 1.1). Two tectonic domains located at the western part of the KRB are exposed in the study area: (i) the western part of the seismically active W-/NW-/NNW-striking KMF and, (ii) the NW striking VGKNFS, traceable for ~80 km with a fault zone width of ~10 km (Biswas, 1993) (Fig. 1.1). The study area covers the KMF zone to the northeast of Karanpur dome, Ghuner dome, Sahera, Mundhan anticline, Jara dome, Jumara dome and Manjal dome. The VGKNFS is located to the west of Nakhatarana and east of Matanomadh.

People, communication and occupation

Various groups and cultures occupy the district of Kachchh. Approximately 80% of its population lives in rural areas, so people depend mostly on agriculture and cattle rearing. The region's economy is agro-based and the region is known for its craftwork. In recent times, the rapid industrialization has been prompted by the development of several major ports in the coastal parts of Kachchh, which has created another window of opportunity for people to earn their livelihoods. The area within the KRB contains a fairly good network of metalled roads. The small towns and villages are also well-connected with a dense network of roads.

Physiography

Physiographically, the Kachchh is primarily divided into several geomorphic zones- the Great Rann and Banni plain, the Island belt, the Wagad highland, Mainland Kachchh and coastal zone of Kachchh. The landscape of Mainland Kachchh is influenced by structural and tectonic fabric. The Kachchh also comprises a vast flat terrain consisting of a barren landscape of the Great Rann of Kachchh and the Banni plains, which are part of a former gulf occupying an E-W trending tectonic depression. The raised mudflat between Mainland Kachchh and the Great Rann is defined as the Banni plain, almost flat, raised at approximately 3-10 m above the level of the Great Rann (Kar, 1995). A later phase of upliftment is evidenced by the presence of gullies and incised fluvial channels on the elevated eastern parts while enormous frequent earthquakes have caused extensive liquefaction to occur (Biswas, 1974).

An E-W trending linear series of four islands defines the Island belt of Kachchh (Biswas, 2016). Geographically it is located to the north of Wagad and Mainland Kachchh. These islands from west to east are the Patcham, the Khadir, the Bela and the Chorar islands (Biswas, 2016). The Wagad highland exposes both Mesozoic and Tertiary age rocks, being situated between Mainland Kachchh and the Island Belt. The northern margin of Wagad is marked by the North Wagad Fault (NWF), while the southern margin is delineated by the SWF (Biswas, 2016, Maurya et al., 2017a). The Mainland Kachchh forms the largest geographic entity in the Kachchh basin with the most rugged and well-developed sequence of Mesozoic and Cenozoic rocks (Biswas, 1993). On the north it is bounded by the KMF forming an E-W trending NHRFZ (Biswas, 2016).

Drainage

Drainage pattern of an area is a reflection of geologic, geomorphologic and climate processes acting in that area. Generally, the drainage pattern of the area is dendritic in nature which typically develops in areas with homogenous lithologies in terms of weathering that provide no preferred direction to the development of stream channels. Also radial drainage pattern is seen around the domes. Three major rivers are forming the main drainage network in the study area. These rivers flow in NE direction and debouches in the Great Rann sub-basin. These rivers, at places, have been affected by the NW-SE trending, sub-parallel faults. The streams show numerous sharp turns which can be explained as stream courses following some pre-existing faults or weak zones that got reactivated in recent past. Due to such reactivations, formation of knick points along north-flowing streams took place.

Where the antecedent streams have encountered the active faults, the streams continue to flow in spite of the active uplifting along the faults, but its path has been deflected due to deformation. The streams show negligible amount of downward incision when they enter in the fault damage zone. Such deflection of drainages has been noted at several locations. Such divergence in the path of the streams have sufficiently leave the active tectonogeomorphic fingerprint. The complex nature of Kachchh mainland is result of streams switching or abandoning outlets as they cross the E-W trending master faults. It suggests that along the transverse fault there is strike slip movement. The N-S, NNW-SSW and NNE-SSW trending straight, trellis and angular drainage pattern respectively that have developed in the area point to the influence of transverse structures. Also, both the lower and the upper order streams trend in N-S, NNW-SSE and NNE-SSW direction, indicating the influence of recent tectonic activities in the area. The response of streams to the transverse faults is seen in the form of sharp angular turns in their courses.

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 month marks the hottest month of the year where the day temperature reaches up to 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 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 and Fauna

The Kachchh district has a wide variety of Acacia trees and also grown 'Gando Bawal'. The Kachchh forests are characterized by thorny and non-thorny tree growth. The flora of Kachchh is distributed in the Central hilly zone, Dry Deciduous zone and the Banni zone. Due to long continue maltreatment, the wild tree growth has become almost entirely confined to thorny species - bawal, kher etc.

The vast land of Kachchh has long seashore and vast desartic 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 asses. 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.

APPROACH AND METHODOLOGY

The western part of the KMF provides a perfect example to study the effect of long-term landscape evolution in response to uplift induced structurally controlled erosion due to differential fault movement. Because of the patchy and isolated exposures of the KMF and lack of neotectonic/geomorphic evidence, survey sites were selected to carry out the GPR-based work across the fault strike. There are abundant exposures of the striated fault planes exposed in the VGKNFS, which are suitable to carry out the paleostress investigations. Detailed structural, geomorphic and shallow subsurface geophysical studies were carried out along the KMF and VGKNFS in western part of KRB (Fig. 1.2).

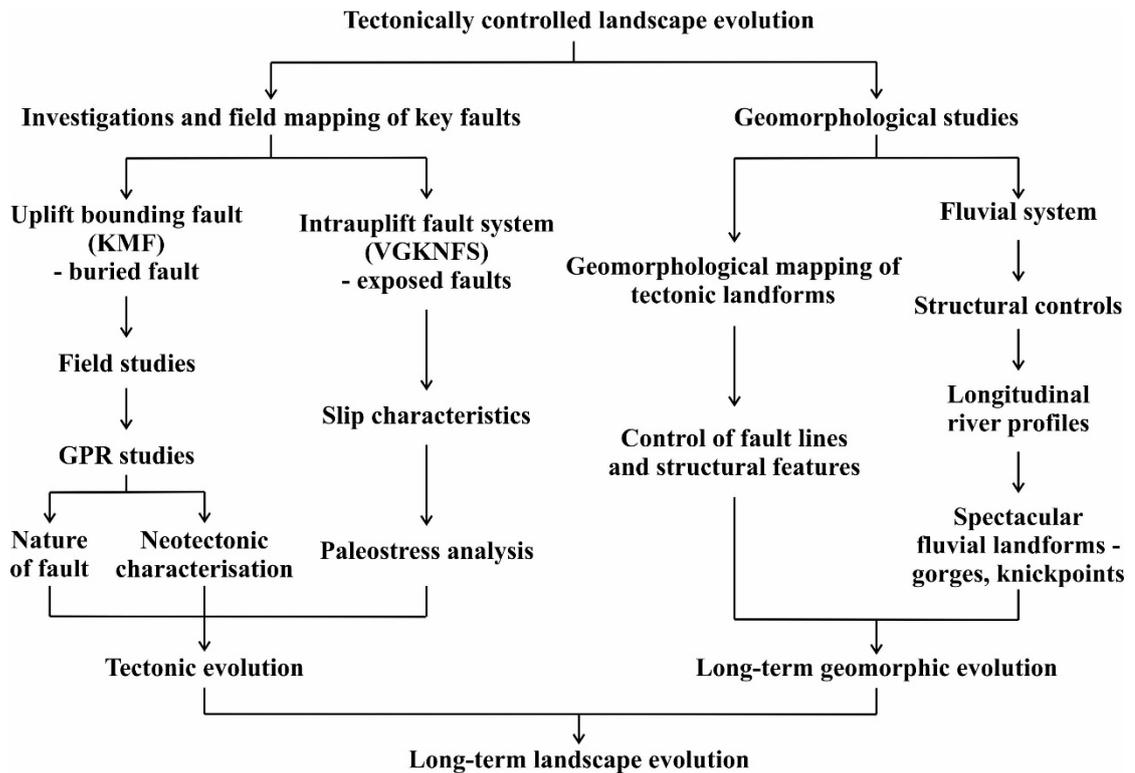


Fig. 1.2. Flow-chart highlighting the approach adopted in the present study.

The detailed methodology adopted for carrying out the present study is as follows:

- Published information on the structural and geomorphic aspects of the KRB were critically studied and evaluated to understand the regional geological setting and their influence on the tectonic set-up of the active fault zones.
- Regional scale geomorphic and structural set-up of the study area was delineated using Survey of India topographic maps and satellite imageries.
- Precise field mapping of various major as well as cross-faults and geomorphic landforms were carried out.
- The structural measurements including fault-slip data were collected in the case of striated fault planes in order to carry out paleostress analysis. Slickenside kinematic indicators were documented in order to determine the slip-sense. The spatial and temporal variation in the paleostress field dominating in the western part of the KRB are observed.
- Geomorphic landforms such as fault scarp, knickpoints, gorge, river incision etc. were documented to understand the effect of periodic tectonic activity on the long-term geomorphic evolution of the study area.

- The high-resolution GPR data were collected to document the neotectonically active nature of the concealed KMF and VGKNFS and related deformation structures and to demonstrate the radar characteristics of the fault deformation zone.
- Geomorphic analysis using topographic profiles, drainage characteristics and longitudinal river profiles was done to understand the impact of periodic uplift along fault zones. Various regional-scale tectonogeomorphic and structural features were highlighted using satellite data.
- The field and GPR data were synthesized to work out the tectonic impact on landscape evolution in response to periodic reactivation of the KMF and VGKNFS.