

CHAPTER 2

REGIONAL GEOLOGICAL SET-UP

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; Shaikh et al., 2020) (Fig. 2.1). The Nagar Parkar Fault (NPF) to the north and North Kathiawar Fault (NKF) to the south act as rift shoulders bounding the KRB (Biswas, 2016). The tectonic framework of the KRB is mainly controlled by large, parallel E-W striking intra-basinal faults. Towards the south, these are – IBF, GF, SWF, KMF (> 1200 m throw) and KHF (~732 m maximum throw) (Biswas, 1993; Maurya et al., 2016) (Fig. 2.1). These major, (sub-)vertical faults show steep flexures and have accommodated large-scale uplifts generated by extension during basin rifting (Late Triassic to Early Jurassic) and are seismically active till today – Island Belt Uplift (IBU), Desalpar Uplift (DU), ~60 km long and ~40 km wide Wagad Uplift (WU), ~193 km long and ~72 km wide Kachchh Mainland Uplift (KMU) (Fig. 2.1) (Biswas, 1993).

The KMU is sub-divided into four structural zones – the NHRFZ along the KMF, Katrol Hill Range Fault Zone (KHRFZ) along the KHF, VGKNFS and Bhuj structural low (Biswas, 1993) (Fig. 2.1). E-W striking, intra-basinal faults are affected and segmented by N, NW, NE, NNW and NNE striking, m to km-scale, transverse faults with dip-/oblique-slip deciphered in the field (Biswas, 1993; Maurya et al., 2003).

TECTONIC EVOLUTIONARY HISTORY

The evolution of the Kachchh rift took place on account of periodic reactivation of the various basement related faults. During the Late Triassic or Early Jurassic, prior to India-Africa separation, the KRB rifted, which generated extensional stresses and experienced constant sedimentation until Late Cretaceous (Biswas, 2016; Shaikh et al., 2020). The rift evolved within the Mid-Proterozoic Aravalli-Delhi fold belt by reactivation of pre-existing faults along NE–SW trend of Delhi fold belt that swings to E–W in Kachchh region (Biswas, 1977; 1987; 1993; 2005). The E-W striking major faults and other subsidiary faults were activated as normal faults on account of extensional

stresses (Biswas, 2016). A series of half-grabens were formed on account of normal faulting successively from north to south (Biswas, 1987; 2005).

The rifting of the KRB then aborted during Late Cretaceous (Biswas, 2016). Drift movement of the Indian plate started with counter-clockwise rotation from Mid-Jurassic period onward after the break-up of the Gondwanaland and India-Africa separation (Biswas, 2016). In the KRB, this caused transtensional motion (Biswas, 2016). From Late Cretaceous to till now, the rifting of the KRB is followed by rift inversion, leading to the formation of intra-basinal uplifts with associated structural lows due to reactivation of earlier normal major faults as reverse faults (Biswas and Khattri, 2002; Shaikh et al., 2020).



Fig. 2.1. (a) Geological map of the Kachchh Rift Basin (KRB), after Shaikh et al. (2020). Geological details are after Biswas (1993). The white inward-pointed double arrows represent the orientation of horizontal maximum compressive stress (S_{Hmax}) compiled from the World Stress Map (WSM) project (Heidbach et al., 2016; 2018). The black dotted lines represent structural contours with 1000 feet (values are in negative) contour interval drawn over the top of Precambrian basement (Biswas, 1993). The black dashed lines represent Bouguer Gravity Anomaly contours in mGal after Geological Survey of India (2000). Red stars indicate major earthquakes in the KRB with focal mechanism solutions (Chung and Gao, 1995; Rastogi et al., 2001). IBF: Island Belt Fault, GDF: Gora Dungar Fault, GF: Gedi Fault, SWF: South Wagad Fault, KMF: Kachchh Mainland Fault, VGKNFS: Vigodi-Gugriana-Khirasra-Netra Fault System, KHF: Katrol Hill Fault, NKF: North Kathiawar Fault. IBU: Island Belt Uplift, DU: Desalpar Uplift, WU: Wagad Uplift, KMU: Kachchh Mainland Uplift, NHRFZ: Northern Hill Range Fault Zone, KHRFZ: Katrol Hill Range Fault Zone. Nature of the uplift-bounding faults is based on Biswas (1993); Patidar et al. (2007); Maurya et al. (2013); (2016); (2017). (b) Seismic hazard zonation map of Gujarat state after BIS 1893-2002. (c) Location of Gujarat state with respect to the Indian plate boundaries depicting various tectonic elements (redrawn after Chatterjee et al., 2013). Red, blue and yellow double arrows denote the direction of relative plate motion at convergent, divergent and transform-fault boundaries respectively.

During the Neogene and Quaternary times, the lows were filled up by thick transgressive marine sediments (Biswas, 1993). During the post-Cretaceous inversion phase, the faults bordering the uplifts were periodically reactivated, thereby promoting the accumulation of Cenozoic sediments (Biswas, 1993).

The present structural style of the KRB indicates large-scale, periodic lithospheric deformation owing to varying regional stress field and also, induced local anomalies in the regional stress pattern (Biswas, 2016). The basin is recognized as one of the best examples of SCR (Stable Continental Region) earthquakes and has been compared with the New Madrid seismic zone (Bodin et al., 2001; Tuttle et al., 2002; Schweig, 2003). The KRB, which is the most earthquake prone intra-plate region in India, falls in the highest seismic risk zone-V in seismic hazard zonation map (BIS, 2002; Choudhury et al., 2018). The KRB is characterized by multiple seismic sources as it has witnessed several devastating, moderate-high magnitude intra-plate earthquakes attributed to periodic tectonic movement along the intra-basinal faults. Few examples are: the 1819

Allah Bund earthquake (M_w 7.8; 15 km focal depth; Bilham, 1999; Rajendran and Rajendran, 2001), 1956 Anjar earthquake (M_w 6.1; 15 km focal depth; Chandra, 1977; Chung and Gao, 1995) and 2001 Bhuj earthquake (M_w 7.7; 23 km focal depth; Bendick et al., 2001). Therefore, a thorough understanding of behavior of the large-scale, regional stress pattern acting upon the KRB is necessary.

However, tectonic evolutionary history of these faults, particularly, in Late Cenozoic and consequent landscape evolution is not known. This has resulted in a general lack of geological database on the fault zones that includes precise fault maps, geomorphologic setting, long-term and short-term slip rates. Tectono-geomorphic Studies are essential to resolve the above geological issues which are critical for seismic hazard estimation and mitigation in the KRB.

Neotectonic, tectono-geomorphic and paleoseismic aspects of the major E striking intra-basinal faults have been widely discussed in literature during the last two decades. Towards the south, these are – ABF (Rajendran and Rajendran, 2001; Padmalal et al., 2019), IBF (Bhattacharya et al., 2019), GF (Maurya et al., 2013), SWF (Kothyari et al., 2016; Maurya et al., 2017), KMF (Chowksey et al., 2011a, b; Shaikh et al., 2019) and KHF (Patidar et al., 2007; 2008). Probabilistic Seismic Hazard Assessment (PSHA) and Deterministic Seismic Hazard Assessment (DSHA) studies have estimated 1.0-1.1 g of maximum acceleration along the major faults in the KRB (Choudhury et al., 2018).

The KRB is located in the hyper-arid belt of NW India that includes the Thar Desert to its north (Fig. 1.1b) resulting in a highly rainfall deficit climatic regime (Machiwal et al., 2016). As a consequence, various rivers show dry channels for the most part of the year with insignificant episodic water flows, lasting for few days during monsoon season. Also, there are no historical records of extreme discharges or floods during historical times, however, several prolonged spells of drought have been common (Machiwal et al., 2016). This together with a long history of devastating earthquakes points to tectonics as the major geological factor in the geological evolution of the KRB.

MESOZOIC STRATIGRAPHY

The Mesozoic rock stratigraphy comprises Late Triassic pre-rift sediments, Jurassic syn-rift sediments and Early Cretaceous post-rift sediments (Biswas, 1978; 1993;

2016). Three lithostratigraphic domains are recognized by distinctive lithological association:

- 1) The Mainland Group,
- 2) The Pachham Group and
- 3) The Eastern Kachchh Group.

The study area falls in the Kachchh Mainland group and its lithostratigraphic classification is presented in Table 2.1. The Mesozoic rocks constitute more than three-fourth of the land area of Kachchh (Biswas, 1978; 1993; 2016). These rocks are divided into four formations which are formally named as the Jhurio, Jumara, Jhuran, and Bhuj formations in ascending order (Table 2.1).

Jhurio Formation

A thick sequence of limestone and shales with bands of 'golden oolites'. The type section occurs in Jhurio hill, in the north-central Mainland (Biswas, 1993) (Table 2.1). The upper part of the formation is made up of thinly-bedded white to cream coloured limestones (pelmicrite and biomicrite), with thin bands of 'golden oolite' (Biswas, 1977). The middle part is composed of thick beds of grey-yellow weathered shales, alternated with thick beds of golden oolitic limestones (Biswas, 1993). The lower part comprises of thin beds of yellow and grey limestone (Biswas, 1993). The physical and biological aspects of the formation indicates littoral to infra-littoral environment (Biswas, 1993). The Formation ranges from Bathonian to lower Callovian (Biswas, 1993).

Jumara Formation

A thick argillaceous formation overlies the Jhurio formation, developed and exposed in the central part of Jumara dome which forms a hill adjacent to the Rann, to the south of Jumara village (Biswas, 1977) (Table 2.1). This formation is richly fossiliferous here and becomes progressively less fossiliferous eastward (Biswas, 1993). It comprises mainly shale with inter-beds of thin marlite, sandstone and siltstone (Biswas, 1993). Upper part is characteristically marked by greenish, glauconitic, oolitic limestone and glauconitic shale inter-beds (Dhosa Oolite Member) (Biswas, 1993). The Dhosa Oolite member consistently marks the top of the formation from west to east across the

Mainland indicating maximum transgression during Jurassic (Biswas, 1993). The thickness of the formation is more or less uniform throughout the area varying between 900 to 950 feet (Biswas, 1993). The age of Jumara Formation ranges between Callovian to Oxfordian (Biswas, 1993).

Table 2.1. Lithostratigraphic classification of the Mesozoic rocks of Kachchh Mainland (modified after Biswas, 2016).

Kachchh Mainland Group		
Member	Formation	Stage
Basalt flows	Deccan Trap	Maastrichtian-Danian
Upper Member: massive sandstones	Bhuj Formation	Albian
Ukra Member: Green glauconitic shale/ferruginous bands		Aptian
Ghuner Member/Lower Member sandstones/shales/ferruginous bands/shales with plant fossils		Hauerivian to Barriasian
Katesar Member: Massive sandstones	Jhuran Formation	Tihonian
Upper Member: fossiliferous sandstones, shales		Kimmeridgian
Middle Member: mainly shales, fossiliferous with sandstone inter-beds		
Lower Member: sandstones/shales/arenaceous limestones		
Hiatus		Oxfordian
Dhosa Oolite Member	Jumara Formation	Callovian
Gypseous Shale Member		
Ridge Sandstone Member		
Shelly Shale Member		
Member G: Thin bedded white and nodular limestone	Jhurio Formation	Aalenian-Bathonian
Member F: Purple sandstones/ Packstones		
Member E: Bedded rusty grainstone with golden oolite		
Member D: Gray shales		
Member C: Brick red weathering rusty grainstone		
Member B: Gray shales		
Member A: Thin bedded yellow white limestones, shales, rusty brown limestones with golden oolites ???		
Basement		

Jhuran Formation

The following higher formation overlying the Dhosa oolite member of Jumara formation and overlain by non-marine sandstone of Bhuj formation (Biswas, 1993) (Table 2.1). It is well exposed in the northern range of the mainland of Kachchh (Biswas, 1993). It shows the uniform lithologic characteristic throughout in Charwar range (Biswas, 1993). In the Jhuran village the upper and lower limit of the formation are very well defined (Biswas, 1999). The shale/sandstone alternation with thin bedded hard calcareous sandstones constitutes the Jhuran Formation overlain by brown and pink sandstone with ferruginous beds which dominated the deltaic Bhuj Formation (Biswas, 1993).

Bhuj Formation

A huge thickness of non-marine sandstones of uniform character comprises the youngest formation of the Mesozoic stratigraphy of Kachchh (Biswas, 1977). This formation is defined by the marine beds of Jhuran formation below and the Deccan trap flows above (Biswas, 1993) (Table 2.1). The lower member is characterized by cyclic repetition of ferruginous or lateritic bands shales and sandstones. The upper member consists of whitish to pale brown, massive, current bedded, coarse grained well-sorted sandstones with kaolinitic shale and ferruginous band alternations at thick intervals (Biswas, 1993). The Ukra member contains olive green glauconitic sandstones, “green sands” and green and gray shales with thin, fossiliferous bands of purple ironstones, ferruginous mudstone, and gray limestone (Biswas, 1993). It is concluded from the lithology, absence of fauna and richness in flora, sedimentary structures, pattern of current-roses, and marine tongues in the down basin direction, that the sediments represent deltaic deposits with distal part (delta front) towards the west and the proximal part (fluvial) to the east in the direction of the land (Biswas, 1993). A Lower Cretaceous (Valanginian) to Santonian time range is assigned for this formation (Biswas, 1977).

TERTIARY STRATIGRAPHY

Tertiary formations of Kachchh are highly fossiliferous containing rich assemblages of different fossil families both mega- and micro-fossils (Table 2.2). These sediments are not disturbed by tectonic movements unlike the Mesozoic sediments

(Biswas, 1993). Tertiary formations are exposed mainly in the coastal plains of the Mainland bordering the central highland where the Mesozoic rocks are exposed. Neogene rocks directly lying over the Paleocene laterites and ferruginous shales, are exposed in the peripheral plains bordering other highlands (Biswas, 1993) (Table 2.2).

Table 2.2. Tertiary stratigraphy of the Kachchh (modified after Biswas, 2016).

Age	Stage	Formation	Lithology
Late Miocene to Pliocene	Kankawatian Super-stage	Sandhan	Sandstones, minor limestone and shale
Burdigalian	Vinjanian	Chhasra	Upper: silty shale Lower: shale/limestone
Aquitainian	Aidaian	Khari nadi	Variegated siltstones and sandstones
Chattian	Waorian	Manyara Fort	Upper: Foram. Limestone/oolite sandstone, Middle: limestone with coral bioherms, Lower: lumpy claystone, gypseous shale
Priabonian	Hiatus	Paraconformity	
Bartonian	Rakhadian	Fulra limestone	Dense foraminiferal limestone
Lutetian	Babian	Harudi	Claystone/limestone
Ypresian	Kakdian	Naredi	Upper: ferruginous claystone. Middle: Assilina limestone. Lower: glauconitic gypseous shale
Thanetian	Madhian	Matanomadh	Laterites and volcanoclastics; tuffaceous shales and sandstones
Maastrichtian to Danian	Deccan Trap	Basalt	Terrestrial lava flows

The Tertiary rocks are best developed in the southwestern Kachchh Mainland (Biswas, 1993). The Tertiary outcrops are always separated from the pre-Tertiary/Deccan Trap by beds of lateritic and volcano-clastic rocks of Paleocene age (Biswas, 1993).

QUATERNARY SEDIMENTS AND NEOTECTONICS

The E-W striking intra-basinal fault zones geomorphologically display the characteristics of a dynamic range-front environment that is evident from the steep faults carps, incised valleys, entrenched meanders and narrow northward-sloping zone of predominantly coarse-grained colluvio-fluvial deposits of Quaternary age that overlaps the fault zones (Patidar et al.2007; Chowksey et al. 2011a, b). All of the fault zones show neotectonic control on the deposition of Quaternary sediments, although the stratigraphic development varies (Patidar et al. 2007, 2008; Chowksey et al. 2010, 2011a, b; Maurya et al. 2013). These sediments provide stratigraphic evidence for pre-miliolite and post-miliolite phases of neotectonic activity along the various faults. OSL dating of sediments that overlap the KMF suggest two major phases of colluvio-fluvial deposition at 100 ka BP and 35–50 ka BP. The central valley formed along the synclinal structure acted as the major sink for the deposition of the Quaternary sediments in Pachcham Island. However, the chronology of Quaternary sediments along the other fault zones is not available. Offsetting of the Quaternary sediments that overlap the KHF indicates multiple surface faulting events during the Holocene (Patidar et al. 2008). However, similar evidence has not yet been found along the KMF, SWF, IBF and GF. Overall, the Quaternary sediments confined within the fault zones clearly indicate the role of dominantly vertical neotectonic movements in the evolution of the landscape.

The fact that the transverse faults offset all of the east–west trending faults, which are the primary stress accumulators in the basin, is a significant feature (Maurya et al. 2003b). Some of the geomorphic anomalies, such as the entrenched meanders, the deformation of the Quaternary sediments, the marked variations in the levels and thicknesses of the Quaternary depositional surface and the tendency of the KMF to transform into a high-angle reverse fault, invariably occur in the vicinity of intersections with the transverse faults. Detailed studies on discontinuous and seismically active faults elsewhere have demonstrated that such faults act as stress concentrators, and that earthquakes may cluster in the vicinity of transverse faults offsetting them. This suggests that future earthquake nucleation along the active faults in the region is most likely to occur in the zones where the east–west trending faults intersect with the transverse faults.