Chapter - 12

DISCUSSION

The Saurashtra peninsula, also known as the Kathiawar uplift located in Gujarat state, western India is a distinct tectono-geomorphic entity bounded by four major faults like North Kathiawar Fault (NKF), extension of West Coast Fault (WCF), extension of Narmada-Son Fault (NSF) and Western Cambay Basin Margin Fault (WCBMF) at north, west, south and east respectively (Biswas, 1987). It is a quadrangular southwest titled uplifted horst block surrounded by three rift basins- viz., Kachchh at the north, Cambay at the east and Narmada at the south along three major Precambrian trends viz., Aravalli trend (NE-SW), Dharwar trend (NNW-SSE) and Satpura trend (ENE-WSW) respectively (Biswas, 1982, 1987). The region comprises oldest Mesozoic sedimentary rocks of lower Cretaceous age overlying the granitic basement and trappean lava flows associated with structurally controlled dykes of late Cretaceous to Paleocene age (Figure 2.2). The Tertiary rocks are exposed in the coastal zone which are mostly buried under younger Quaternary deposits that includes miliolites (Merh, 1995). The miliolites are of marine, aeolian and fluvial origin and represent multiple depositional phases (Merh, 1995). Holocene deposits consist of mainly mudflats, alluvial deposits and beach dune complexes overlying the miliolitic limestone deposits.

The geophysical studies (Table 2.2) suggest crustal heterogeneity in some parts of Saurashtra. The crustal thickness in Saurashtra is more towards northern part than southern part because of southward tilt of horst block. The region is considered tectonically dynamic and is included in seismic zone III and IV of Seismic Zoning Map of India (BIS, 2002). The seismicity pattern is characterized by numerous episodes of earthquake swarm activities over last several decades (Figure 2.2). The major concentrations of the swarm type of earthquake activities epicenters are found to occur around Bhavnagar in the east, Jamnagar in the northwest and Talala in the southwest (Figure 2.2).

The southern margin of Saurashtra region is affected by Deccan volcanism, plate fragmentation, structurally controlled dyke swarms, extension of crustal scale discontinuity of NSF and earthquake swarm activity. However, deep geophysical data from central Saurashtra also shows discontinuities and variations in crustal characteristics

(Chopra et al., 2014). However, published data of morphotectonic set up and neotectonics of SW Saurashtra is scanty. The present study was, therefore, carried out in the southwestern part of the Saurashtra region. Geomorphologic characterization of dyke swarms, trappean lava flows, Tertiary rocks and Quaternary deposits in the study area is done and mapped during the course of the present study. The study area is drained by ten major river basins viz., Hiran, Somat, Singwada, Sangawadi, Rupen, Machundri, Rawal, Malan, Raidi and Dhantarvadi. These rivers flow from the mountainous terrain in the north flow southwards to meet the Arabian Sea.

The main components of the present study are- geomorphology of the area using remote sensing and field data to demarcate the geological controls on the drainage configuration and reconstructing landscape evolution. In addition, paleostress studies and morphotectonic analysis were carried out for the faults mapped in the trappean terrain. Based on topographical contrasts, geomorphological characteristics and structural elements, the study was divided into two domains viz., morphotectonic domain-I and morphotectonic domain-II (Figure 3.1). Morphotectonic domain-I includes the eastern part of the study area which is drained by three major river basins viz., Malan, Raidi and Dhantarvadi River. It comprises undulating rocky terrain with structurally controlled dykes, SE tilted trappean lava flows, Tertiary rocks and Quaternary deposits (Figure 3.2). Whereas, morphotectonic domain-II, western part of the study area, covers seven major drainage basins such as Hiran, Somat, Singwada, Sanagawadi, Rupen, Machundri and Rawal. This domain contains trappean basalts, patchy exposure of Tertiary rocks, extensively covered various depositional phases of miliolitic limestone and recent coastal deposits (Figure 3.4).

12.1 TECTONIC INFLUENCES ON LANDSCAPE

12.1.1 Morphotectonic domain- I

The eastern part of the study area covers an approximate area of about 1183 km^2 comprising three S to SSE flowing major rivers originating in rugged topography developed over Deccan traps and continues to drain along south sloping topography comprising of Tertiary deposits up to coastal area consisting of Late Quaternary miliolite deposits. Majority of the area is covered by trappean dyke swarms trending NE to NNE extending from the further east of the study area. The northern part of the domain comprises southwest tilted lava flows with northwest facing escarpments and dyke ridges. While southern part is mainly covered by Tertiary deposits overlying pediment surface up to the coast. The coastline in this domain consists of intertidal flats and alternate exposure of miliolite cliffs and beach dune complexes.

This domain is divisible into three distinct geomorphological zones viz. the upland zone consisting of Deccan Trap, gently southward sloping pediment zone with thin veneer of discontinuous alluvium and coastal zone (Figure 3.2). The upland zone covers northern part of the domain characterized by hilly topography developed over trappean basaltic flows profusely intruded with dyke swarm ridges trending ENE-WSW to NE-SW that parallels with the NSF trend separated by low lying rocky surfaces. The ridges are found to be preferentially oriented in NE-SW direction that gradually swings to NNE-SSW towards the coastline. Almost all such ridges are found to be asymmetrical with prominent NW facing escarpment and gentle slope towards SE. These ridges are typical cuesta ridges that have developed over SE to ESE dipping basaltic flows. The narrow E-W trending pediment surface occupies the area between the upland zone and the coastline in the south is gently sloping pediment surface formed due prolonged erosion and non-deposition. The pediment surface is formed over the Deccan Traps, Laterites and SE to S dipping Tertiary rocks. It shows a strong structurally southward slope towards the coastline that is attributed to the general southwards dips of the pre-Quaternary rocks. The rocks are extensively exposed along the streams as it is mostly covered by thin and discontinuous sandy alluvial deposit. In addition, Tertiary rocks are found to crop out in the mudflats around Jafarabad and Pipavav port and sheet miliolites are encountered along the lower reaches of Malan River. The coastal zone is very narrow and comprises a thin coast parallel strip of Quaternary miliolites. However, the coastal zone is found to be wider in the creek systems developed notably around Jafarabad and Pipavav. The creeks show extensive mudflats in their vicinity, while the rest of the coastline is marked by high vertical cliffs formed in miliolites. Several coastal erosional features like sea caves and notches are developed in the coastal cliffs and few small sandy beaches break the monotony of the miliolite cliffs along the coastline. Two raised notches dating back to ~125 ka and ~6ka have been reported from the coastal cliffs around Jafarabad (Pant and Juyal, 1993). These notches indicate ~7 m uplift of the coastal zone during the Late Quaternary (Pant and Juyal, 1993).

Several lineaments and ridges observed nearby fault (F1) trend ~NE, and very rare eastward trending ridges are observed in the surrounding regions. A discontinuous ridge SW of Katar village, W of Nana Barman village, trending ~E has been observed. The extensive fieldwork revealed that such ridges are devoid of strike-slip faults. However, faults (F2 and F3) is normal dextral and normal sinistral nature with few evidences showing strike-slip component. This is indicative of reactivation of all these faults showing multiple striations and developed over fault planes. At several places, some geomorphic landforms formed due to strike-slip faults such as deflected streams can be noted. The evidences from all the fault slip data reveals that the area has undergone multiple reactivation phase post-Deccan trap period. The stress pattern during Cretaceous period and post-Deccan trap time shows NE to NNE compression.

The slip characteristics of the faults provide an insight into the tectonic set up of the morphotectonic domain-I. Numerous faults, shear zones and brittle shear planes were mapped in the trappean terrain and paleostress analysis of fault-slip data were carried out for previously unreported and unmapped faults. Paleostress analysis carried out using fault slip data to define the orientation of principal stress axes. In this domain, three major faults showing prominent striation-bearing fault planes and brittle shear P-planes almost perpendicular to those fault planes, i.e., on ~ horizontal planes were identified, mapped and analyzed inferred stress trend. Fault (F1) at Katar village, near Rajula town is E-W trending oblique slip reverse fault with sinistral slip. The detailed fault slip analysis clearly suggests oblique slip reverse faulting with sinistral slip to be the dominant deformation style as shown by phase 2 deformation event in F1. The faulting appears to correlate with the phase of tectonic activity after the main extrusive event (Rao, 1971). Oblique faulting with reverse component indicates transpressional stress regime (due to northward movement of Indian plate) along the Katar Fault (F1). The post Deccan trap movement along Katar Fault (F1) matches with the east to southeastward tilting of the trappean lava flows occurring around Rajula.

The NE-SW trending faults F2 and F3 shows oblique slip normal fault with dextral slip and normal fault with sinistral slip respectively. The SHmax trend obtained from these faults varies. However, all the SHmax result ranges between N20^{o} E and N50^{o} E showing maximum compression from NE-SW direction. The joint sets data of Tertiary rocks were collected from the best exposures found in river section shows orthogonal and conjugate joint sets. The paleostress analysis carried out for 65 NNE to NE trending joint plane infers SHmax trend as N46° E suggesting NE compression. While NNW and NW joint plane measurements indicate N134° E SHmax trend inferring NW compression. The Quaternary miliolite joint sets data are largely observed in the morphotectonic domain-II inferring NE compression. The paleostress analysis results of all the faults and joint sets data shows mostly compression from NE-SW direction. However, compressional regime started after the collision of Indian plate with Eurasian plate. Therefore, the possibility of the reactivation of faults with multiple slip sense indicates post-Deccan trap stress setting. The Tertiary and Quaternary rocks shows NE SHmax trend which is associated with the compression of ongoing movement of Indian plate towards NNE to NE.

The Saurashtra region lies in the intraplate region experiencing very low deformation rate and hence the DEM analysis is a convenient method that has been carried out for this study along with detailed field investigations. The slope analysis of morphotectonic domain-I shows dyke swarm ridges that display north to northwest facing escarpments and gentle southeastward slope. The lineaments in this domain with area >1500 km^2 is developed mostly over trappean terrain where dyke swarms swings southward near Malan River and straight flowing river courses that might indicate the influence of deep seated fractures or faults. Rivers has always being very sensitive to landscape changes controlling channel incision, stream deflections and geometry in tectonically active region (Pérez-Peña et al., 2010). The south to SSE flowing three major rivers investigated shows dendritic to trellis and rectangular pattern due to structural features like conjugate joint pattern, faults, shear zones, dyke ridges and strike (cuesta) ridges and valleys. The parallel long drainages flowing in the Tertiary deposited terrain infers southward tectonic slope. The Dhantarvadi drainage basin covers the largest area showing significant variation in channel course from flowing eastward to rotating southward around the dyke ridges swinging from ENE-WSW to NE-SW. The concave upward river profiles shows several slope breaks in the upland zone due to deep incised bedrock valleys with knickpoints, anomalous channel bends in dyke swarm terrain and trappean erosion near fault and brittle shear zones. The small streams in pediment surface flowing coastward along the tectonic slope are also controlled by faults observed between Malan and Raidi drainage basin. The presence of faults and dyke ridges adjusting the drainages, rectangular to trellis streams flowing in upland zone, sudden slope change, and straight channels over flat topography in pediment surface with large mudflats inundating landward are the prime evidences in the domain. This clearly indicates a strong control of the structural elements on the drainage configuration and role of tectonics in the landscape development.

The geomorphic characteristics, fluvial system and field observations shows evidences for understanding the present-day landscape. However, the enduring topographic variations and drainage basin framework developed over the diverse terrains of morphotectonic domain-I measured quantitatively for precise results to know the relative tectonics and to document tectonic impact on the landscape changes (Horton, 1945; Strahler, 1957; Biswas, 1999; Tsodoulos et al., 2008). Geomorphic indices calculated for all three drainage basins infer strong structurally distorted and tectonically controlled landscape. The higher drainage density of the Raidi River show that the area is highly dissected which is in contrast to the semiarid climate and ephemeral nature of the rivers implying structural control. Even the high mean bifurcation ratio is of Raidi River which is in conformity with the dominant influence of structure on drainage characteristics as revealed by the anomalous stream bends and drainage configuration. The Malan River shows extremely elongated basin that is associated with relatively high influence of tectonic activity. This is because Malan river is controlled by NNE trending fault (F2) that divides undulated hilly topography to the west and dyke swarm ridges to the east in the westernmost margin of domain-I.

The morphotectonic parameters calculated for knowing the landscape change and tectonically active zones in this domain infers that the middle reaches of all the rivers and the basin area is structurally controlled by dykes and faults. The stream length gradient index results shows higher stream erosion due to southward tectonic slope and sudden breaks in channel gradient at the fault zone. The anomalous peaks suggest the possibility of recent tectonic activities on the trappean lithology due to fault zones. The dominant influence of SE dipping trappean lava flows observed along with fault controlled lithology and drainages in Raidi basin. The V-shaped valleys indicate the tectonically uplifted terrain consisting tilted trappean lava flows and faulting along dyke ridges and some offsetting dykes. These processes have also resulted in tectonic tilt of the drainage basin towards SW to W resulting into shifting of main channel and negligence of streams. However, Raidi River shows very high asymmetric factor exhibiting main trunk channel move eastward along the tectonic tilt. The tectonic slope shows fragmentation in this domain due to strong influence of structural attributes resulting in the development of the landscape. Evidences like elongated ridges controlling drainages, faults with prominent multiple striations in trappean lithology, V-shaped valleys in upper and middle reaches, knickpoints and rapids, primary and secondary joint sets in Tertiary rocks and Quaternary miliolite cliffs with notches, sea caves and beds dipping landward are distinguished. All these major evidences show that this domain is highly dissection by fluvial activities, tectonically uplifted and still at very youthful stage of basin development.

12.1.2 Morphotectonic domain-II

The morphotectonic domain-II in the present study consists of rocks of Deccan trap formation covering northern half of the drainage basins while miliolite deposits occupy the lower half of the river basins. The entire domain covers an area about ~3000 km^2 with seven major southward flowing drainages flowing in trappean highlands and miliolitic terrain. Overall, the domain is divided into three major geomorphic zones – the upland zone showing rugged hilly topography, the southward sloping buried pediment zone occupied miliolites and the narrow coastal zone. The upland zone contains erosional conical and circular hills, abundant linear dyke ridges protruding over trappean surface. Field investigations were limited in the upland zone as it falls under reserved forest of Gir National park. However, detailed remote sensing analysis, lineament analysis, geomorphic studies and morphotectonic analysis were carried out of the upland zone. The buried pediment zone is entirely covered by various depositional phases of Quaternary miliolite deposits and patches of Tertiary rocks exposed at few locations. This zone is extensively studied which examined the morphological characteristics of the aeolianite ridges, sheet miliolites and aeolian dune deposits which are dominantly exposed in this domain. The gently sloping pediment surface exhibits few undulating topography due to the presence of the aeolianite ridges which are identified with the help of remote sensing data, topographic profiles and field surveys. The coastal zone consists of coastal dune deposits, intertidal flats, shore platforms, extension of aeolinite ridges and present day beach dune complexes. The height of the miliolite cliffs rises as we go from Veraval in the west up to Diu Island in the east and intertidal flats are comparatively smaller than domain-I. For the present study, these rivers are divided into two categories. Category I include large rivers originating in trappean terrain like Hiran, Singwada, Machundri and Rawal River. Category II includes three small drainage basins, viz., Somat, Sangawadi and Rupen River flowing mostly in miliolitic terrain.

All the analyses results shows that the drainages show diverse channel characteristics and mostly controlled by trappean dyke ridges and hills in upland zone while the aeolianites ridges and aeolian dune complex terrain controls the streams in buried pediment zone. The aeolianites ridges play major role in the geomorphic and morphotectonic evolution of this domain. The sharp 90º river bends are due to the obstruction of these ridges that are eroded and later retreated forming large knickpoints and sudden gradient change. These ridges close to coastal zone are retreated showing deep miliolitic channel incision. However, innermost ridges are eroded back upstream from trap-miliolite interface shows trappean basalt overlain by sheet miliolites. These evidences interpret the presence of multiple parallel aeolianites ridges deposited (sub) parallel to the present coastline. The straight channels in the buried pediment zone showing steep cliff sections noticed predominantly in wide bedrock channel with strong miliolitic incision. This is a clear evidence of strong post-miliolitic tectonic uplift as river deeply incising miliolitic limestone. Significant deep incised valleys in the gently sloping planar topography and straight courses with irregular channel bends around aeolianites ridges are indicative of tectonic uplift during Quaternary period. The field evidences corresponding to the remote sensing analyses, fluvial characteristics gave prominent evidences that infer the geomorphic evolution of the domain.

Category I rivers, Hiran, Singwada, Machundri and Rawal, originate in extremely rugged terrain at higher elevated area eroding the basaltic flows and protruding linear ridges. The drainage basin topography shows undulating upland terrain with a prominent mountain front scarp and extending dyke ridges, moderate to gently sloping planar topography covered by Quaternary deposits, mudflat at the back of coastal cliff up to ~5 to 7 m high. Slope data exhibits steep to moderate slope due to the sharp incision of rivers forming deep valleys and gorges, erosional lava flows, receding trappean hill facets and dyke ridges creating highly fragmented upland zone. However, the regional slope is towards south to southwest besides trappean hills and coast parallel and subparallel aeolianite ridges. The lineament analysis suggests two dominant trends, NE-SW and WNW-ESE indicating the dyke ridges, faults and straight channel courses. Machundri and Rawal River flows on a straight course compared to Hiran and Singwada River showing sinuous reaches. However, strong structural distortion is observed in Singwada River as trappean dykes and aeolianites ridges are controlling the drainages in upland zone and buried pediment zone respectively. On the contrary, Rawal River showing higher values of drainage density, stream frequency and drainage texture indicating largely dissected terrain formed by cross-cutting dyke ridges and trappean hills over basaltic flows. This may be due to basin affected by fault zones, brittle shear planes and dyke swarms found to its east. The highly elongated basin shape infers that all the basin area is controlled by homogenous impermeable trappean lithology in the upper half and Quaternary miliolite deposits in the lower half of the basin. The outcomes of geomorphic indices infers that the lower reaches of Hiran and Singwada river is mainly controlled by coast parallel and E-W trending aeolianites ridges. While, Machundri and Rawal river shows strong influence of structural elements affected by fault controlled topography of domain-I.

The stream length gradient (SL) index results of category-I rivers shows several slope breaks in the profile suggestive of structurally controlled dykes, trap-miliolite interface, variation in different phases of miliolite deposits, and trappean hills, tectonic uplift or presence of fault/deep seated fault. The Vf ratio calculated shows deep V-shaped valleys in the upland terrain due to strong channel incision in upland zone. However, highly incised channel valleys in the gently sloping topography are suggestive of strong ongoing channel incision due to post-miliolitic tectonic uplift. All the drainage basins are highly asymmetric except Hiran River basin. However, Singwada River shows different tectonic tilt compared to all other basin inferring the role of tectonic activity nearby in developing the basin landscape. The hypsometric integral values suggests that the rivers flowing in highly dissected terrain are at very young stage of channel erosion and basin area still needs long time to obtain the equilibrium. The formation of knickpoints, potholes and deep incised V-shaped valleys due to ongoing channel erosion in trappean and miliolitic terrain clearly indicates the young river courses. The deep incision by the channel in miliolites forming these erosional features even in the lower reaches suggest post-miliolitic tectonic uplift. These analyses inferred that the domain-II shows tectonically active zones that are sensitive to geomorphic and landscape evolution. Overall, the presence of deep incised valleys, sharp anomalous channel bends, knickpoints, rapids, abrupt gradient change, sudden change of river course and drainage adjustment to the gently sloping miliolitic terrain infers that the area is affected by coastal uplift, subsurface structures or earthquake swarm activities.

Category-II rivers flowing mostly in miliolitic terrain are small rivers compared to category-I. They originates in trappean terrain, however, the maximum part of the basin area is occupied by Quaternary miliolite deposits. The gently sloping buried pediment zone shows two prominent slope trends mainly towards ~N and ~S. This infers the presence of aeolianite ridges with having one leeside and one windward side. The lineaments are identified in this zone mostly trending ~E-W and ~N-S representing aeolianite ridges trend and anomalous straight channel courses. Geomorphic indices computed shows significant results pointing towards the influence of tectonic activity on drainage configuration. This inference is based on the fact the area shows semiarid climate and these rivers are strongly ephemeral. However, among all three rivers, Sangawadi shows higher drainage density and bifurcation ratio values suggesting that the basin area shows comparatively high dissected terrain.

The drainage basins are found to be moderately asymmetrical which is noticeable from the preferential concentration of tributary streams on one side of the trunk stream. The tectonic tilt towards southwest of Somat and Rupen river while Sangawadi shows southward channel shift indicating the role of tectonic activity around basin area. Among all seven basins in this domain, Singwada and Sangawadi River shows basin tilt towards east to southeast infers that these drainage basins are affected by tectonic uplift. This assumes that the river flowing in the central part of the domain is either influenced of deep seated faults or fractures fragmenting the ground tilt within the domain or unknown surface faults that needs to be mapped. The V-shaped valleys in buried pediment zone indicates the area is tectonically uplifted forming deep incised valleys in the Quaternary deposited gently sloping terrain. The hypsometric integral values suggests lesser degree of dissection and at youthful stage of channel erosion compared to large rivers. This is also attested by the fact that these three river basins show lower drainage densities and their most part are developed over miliolites of late Quaternary age. The hypsometric curve shows that the rivers are very young and moderately eroded as evidenced by erosional landforms like knickpoints/waterfalls, rapids and deeply incised valleys.

12.2 MORPHOTECTONIC EVOLUTION OF SW SAURASHTRA

12.2.1 Paleostress scenario

The deformation of the Deccan Trap is not yet understood though structural influences have been emphasized based on dyke patterns. Post-Deccan Trap intrusive activity evidenced by the large Girnar intrusive to the NW of Rajula area caused some syn-intrusive deformation of the basaltic lava flows. The Girnar intrusive has been extensively studied for its petrological and mineralogical characteristics (Mathur et al., 1926; Bose, 1973; Paul et al., 1977). But, the detailed structural studies are not available. However, few radial faults within the intrusive, a circular pattern of faults around the intrusive mass and radial dips of the surrounding trappean lava flows are reported (Mathur et al., 1926; Wellman and McElhinny, 1970). This testifies to the structural deformation of the Deccan Trap lava flows and the stresses induced by the intrusive activity after the Deccan Volcanism. The stresses caused by intrusive activity also caused deformation of dykes as far as Gondal, Savarkundla and Amreli (Mathur et al., 1926; Sethna et al., 2001).

Extensional stresses would be expected in SW Saurashtra before the Indian plate collided with the Eurasian plate ~ 55 Ma back (Mukherjee, 2015). After the collision, compressive regime has prevailed that produced NE, NW and ENE lineaments and fault sets in south to southwest Saurashtra. These lineaments and fault sets of different major trends has been observed in morphotectonic domain-I mainly in Rajula and surrounding areas. The offshore region shows several inversion structures because of transpressional and transtensional strike-slip movement (Pandey et al., 2013). In this domain, most of the brittle shear planes show sinistral slip suggesting overall transpressional regime. The T-Tecto software separated the heterogeneous fault-slip data into homogeneous subsets of Phase 1 and Phase 2 deformation events of E-W trending Katar Fault (F1).Phase 2 deformation event, which shows the ~NE-SW trend of SHmax is consistent with the results of Gowd and Rao (1992), Khadkikar (2002), and Bhonde and Bhatt (2009). The NE-SW trend of SHmax may have prevailed under the transpressive stress regime after the collision of the Indian plate with the Eurasian plate and may have persisted in Saurashtra till Quaternary as indicated by the work of Bhonde and Bhatt (2009) and Khadkikar (2002) on neotectonic joints found in Quaternary miliolite deposits in the Saurashtra coastal belt. In fault (F1), the local deviation in the stress field is exemplified by the NW-SE trend of the phase 1 deformation event which may be due to the local perturbation in the regional stress field (Vanik et al., 2018). Bhonde and Bhatt (2009) also reported deviation from the NE-SW trend as indicated by NE-SW to E-W and NNE-SSW to NW-SE. Several SHmax trends observed in the field suggest complex stress pattern in Saurashtra showing two sets of oblique slip striation trends in a single outcrop generated by multiple deformation events (Vanik et al., 2018). However, this study suggests that, an overall transpressive stress regime has prevailed that caused the reverse sinistral slip at various faults mapped in domain-I.

The results of Phase 2 deformation event of fault slip analysis near Katar ridge in fault (F1) using T-Tecto ($\sigma1$ trend: N53° E, plunge: 0°, $\sigma2$ trend: N292° E, plunge: 90°; $\sigma3$ trend N142° E, plunge: 0°) matches also with the other faults that has been documented from nearby regions (Vanik et al., 2018). However, few faults do not match with east trend as observed in fault (F1). Deformation sequence in field-scale has so far not been worked out by any structural geologists. The northward movement of the Indian plate probably produced a transpression in the southern Saurashtra. A strike-slip component of transpression might get predominant at fault (F1). While other faults shows oblique slip normal fault with dextral and sinistral slips. However, these faults show the evidences of strike-slip nature developed in the fault-plane surface and at few mineral veins. Transpression involves shortening (thickening) or extension (thinning) component to the steeply dipping or sub-vertical deformation zone favoring lateral extrusion (Dewey et al., 1998; Fossen and Tikoff, 1998) along with uplift/subsidence (Sanderson and Marchini, 1984). The steeply dipping fault plane surface observed on the top of the ridge possibly indicates bulging/thickening by transpression. The faults are devoid of gouge, breccia and melts. There was no visual effect of shear heating/local metamorphism due to faulting (Vanik et al., 2018)

A careful review of the sparse structural information available suggests that the stresses induced by the Girnar intrusive may be much more extensive than documented till now. The swinging of structural grain evidenced by the dyke swarm as ENE-WSW around Rajula possibly resulted due to regional scale stresses caused by the large Girnar intrusive. This suggests that the eastward tilting of the basaltic flows around Rajula also occurred during this phase (Vanik et al., 2018). Field observation during the present study shows that the E-W trending Katar Fault cuts across the NE-SW strike of the dyke swarm around Rajula. The fault also offsets the NE-SW trending ridge consisting of eastward tilted trappean flows at Katar village (Vanik et al., 2018). We therefore attribute the faulting along mapped faults to transpressive phase of tectonic activity after the swinging of the dyke swarm and tilting of the trappean flows (Vanik et al., 2018).

Gowd and Rao (1992) determined N23° E trend of the horizontal maximum compressive stress (SHmax) by borehole breakouts, hydro-fracturing and focal mechanisms from the Indian peninsula. SHmax results are also obtained by borehole data of Kundan et al., (2017) asN7° E in one well and as N40° E in another well drilled in Kachchh-Saurashtra basin (Kundan et al., 2017). Khadkikar (2002) also reported NE trending SHmax from studies on neotectonic joints at SE Saurashtra. Bhonde and Bhatt (2009) confirm the mean NE trend of SHmax from the coastline of south Saurashtra. The major stress trends plotted in the offshore region (I) $\sigma 1$: N7° E and (II) $\sigma 1$: N40° E differs from the stress tensors of the present study area i.e., $\sigma 1$: N53° E, N20° E to N42° E and N30° E. The difference in orientation between maximum horizontal stresses ($\sigma 1$) of the study area to that to offshore region is (I) N46° E, N13° E to N35° E, N23° E and (II) N13° E, N20° E to N2° E, N10° E. This indicates that from the offshore region into the Rajula area, SHmax (corresponds to $\sigma 1$) underwent a rotation during Tertiary.

The tectonic evolution and the shape of the Saurashtra peninsula is linked to the regional events of breakup of the western margin of Indian plate as it separated from the Gondwanaland and rapidly drifted northward to collide with the Eurasian plate spanning a total period of approximately 160 My (Chatterjee and Bajpai, 2016). The motion of the Indian plate was most rapid (up to 20 cm/yr) during the 67-52 Ma time period (Mckenzie and Sclater, 1971; Yoshida and Hamano, 2015; Chatterjee and Bajpai, 2016) which encompasses the events of Deccan volcanism, separation of Seychelles (~64 Ma), initiation of spreading at Carlsberg ridge at ~63.4 Ma (Collier et al., 2008; van Hinsbergen et al., 2011) and post trappean intrusive activity in Saurashtra. The rapid movement of the plate has been linked to the acceleration provided by the rise of Reunion plume which is also responsible for the Deccan Volcanism, thinning of crust, slab pull and/or ridge push (Collier et al., 2008; Cande and Stegman, 2011). Also, the Indian plate was approximately 1000 km away from the Reunion plume at the time of separation of Seychelles (Chatterjee and Bajpai, 2016). Onset of India-Asia collision at ~55 Ma gradually slowed down the motion to 5 cm/year by ~52 Ma (Chatterjee and Bajpai, 2016).

As discussed above, the continental margin of Saurashtra suffered significant tectonic activity during the northward drift of the Indian plate. However, the transpressional stress regime occurred only during the collision of the Indian plate and the Eurasian plate and enduring till date in the far north (Chatterjee and Bajpai, 2016). The formation of the faults and its further reactivation under transpression is suggested by our fault slip analysis (Vanik et al., 2018). In view of this, it is inferred that these faults were formed due to the onset of compression induced by the collision of the Indian plate. We suggest that the transpression could have been facilitated by the syn-collisional rotation of the Indian plate (Biswas, 1982). Moreover, the E-W orientation of the Katar Fault, perpendicular to the northward directed compression is favorable for transpression induced tectonic activity along the fault (Vanik et al., 2018).

The faults appears to have been reactivated multiple times as the same stress scenario continued to exist through most part of the Cenozoic as the Indian plate pushed northward due to the spreading of the Carlsberg ridge. We believe that this is a distinct possibility as the highly fragmented western continental margin of India comprises of several faults, which were reactivated multiple times during the Cenozoic (Biswas, 1987; Merh, 1995; Maurya et al., 2000; 2017). Our field studies further eastward along the trend of the Katar Fault also revealed evidence of tectonic reactivation. The thin band of Miocene rocks (Gaj Formation) fringing the Deccan trap shows southward dip along the inferred eastward trace of the fault, pointing to a post-Miocene phase of reactivation. The outcrops of the Middle Pleistocene – Holocene miliolite deposits are also limited to ~5 km south of the fault line. Significantly, the miliolites show two raised notches dated to ~125 ka BP and 6 ka BP, along the coastline of Jafarabad (~16 km S of the study area) which suggests 7 m coastal margin uplift after correcting for the sea level fluctuation since ~125 Ka (Juyal et al., 1995). The eastward trace of the Katar Fault correlates with the straight E-W trending margin of a landward indentation of the coastline. The recent mudflats abruptly terminate along the line indicating influence on the coastal geomorphology. This together with recent earthquake swarm activity to the north and west of Rajula suggests neotectonically active environment in and around the immediate vicinity of the fault zones (Vanik et al., 2018). A further detailed tectonic study is warranted to fully comprehend the deformation of Deccan traps in compressional stress regime in Saurashtra and to unambiguously link these faults and other faults to neotectonic and landscape evolution of the area.

12.2.2 Neotectonic evolution

The erosional landforms in response to the tectonic uplift is observed along several major rivers flowing southward in a gently sloping landscape. From the previously discussed outcomes of the geomorphic analyses of domain-II, it is evident that the presence of aeolianite ridges has impacted the Quaternary landscape. The formation of aeolianite ridges in the SW Saurashtra can be assumed by the chronological data already published (Baskaran et al., 1986, 1987, 1989; Sharma et al., 2017). However, the age of the specific miliolite depositional phase are yet to be understood. The aeolianites around the globe is mostly studied as a Quaternary coastal barriers mainly to know the past climate and sea level positions (Cooper and Pilkey, 2002; Bateman et al., 2004; Elmejdoub et al., 2011; Mauz et al., 2013). In the present study, aeolianites are dated older than ~125 ka (Baskaran et al., 1986, 1987, 1989; Sharma et al., 2017) which assumes that the aeolian deposition might have stopped at last glacial stage, beginning of warmer period i.e., penultimate interglacial period. These aeolian deposits are largely controlled by the trappean lava flows retreating facing the hilly facets. These depositions also depends on the wind direction and strength, climate and precipitation (Dasgupta and Bandhopadhyay, 2008). The oldest aeolianite ridge is dated back ~235 ka that comes under Marine Isotopic Stage (MIS) stage 7 characterized by several cold and warm period fluctuations. However, in Diu Island, youngest aeolianite deposition were dated ~126±12 ka (Sharma et al., 2017). This indicates that during the deposition of these ridges and the ongoing phenomena of transgression and regression, the climate aridity was very high. During middle Pleistocene period, dynamic environment change from cold to warm were recorded (Head and Gibbard, 2005). During this phase, the terrestrial regions started flooding resulting in the initiation of fluvial activities (Meinsen et al., 2011; Winsemann et al., 2016). The drainage development in the present study might have been initiated during late Pleistocene period resulting in fluvial reworking of the aeolianite ridges later. The valley-filled/sheet miliolites overlying cross-bedded aeolianites incised deeply by rivers suggestive of post-miliolitic tectonic uplift. Few studies have already concluded the tectonic instability of coastal area and 0.12 to 0.58 mm/year coastal upliftment in SW Saurashtra region during Quaternary time (Baskaran et al., 1989). In addition, the northward shifting Saurashtra Fault or extension of WCF passes to the south of the study area along the shoreline equivalent to Precambrian Dharwar trend (Gowd et al., 1996; Biswas, 1987).

The combined data about the tectonic and geomorphic set up, structural setting, extensive field exploration, fault slip analysis and morphological characteristics of aeolianite ridges correlated with previously published data about seismotectonic and coastal tectonics data suggests that the study area is highly fragmented associated with the reactivation of all the faults and brittle shear planes, variation in tectonic tilting within the drainage basins, topographical contrast associated with structural elements controlling the present-day landscape. The nature of faults and slip sense indicates the faults have been reactivated multiple times in extensional as well as compressional regime. The compressive stress rotation from NE-SW to NNE-SSW is linked with the Indian-Eurasian plate collision and thereby ongoing NE compression. These structural data suggests that the structurally controlled rugged youthful terrain is responsible for the landscape evolution of domain-I. Evidences like massive knickpoints, rapids, potholes, abrupt elevation change, sharp bending of river channels, stream offsets, drainage basin asymmetry, narrow gorges and epicenter of the past earthquakes indicates neotectonism in the study area. Overall, the SW Saurashtra is tectonically active region experiencing post Deccan trap reactivation of faults, post-miliolitic uplift forming string channel incision and diverse tectonic tilted region within the study area. Such evidences attained in the present study attributed in reconstructing the morphotectonic landscape evolution of the SW Saurashtra and generating a renewed geomorphic map that might be helpful for forthcoming detailed geological and geomorphic investigations.

The region is affected by the recurring shocks of earthquake swarm activities in the trappean basalts (Bhattacharya et al., 2004) suggesting dominant role of neotectonic movements in the evolution of landscape (Vanik et al., 2021). Mechanism of repeated earthquake swarms in Saurashtra recorded over almost the last hundred years had remained enigmatic (Rastogi et al., 2013). Such swarm activity has also occurred in the trappean area in 2016-18 in the southern part of mainland Gujarat located to the east of Saurashtra (Sateesh et al., 2019). It is interesting to note that earthquake swarm activity is noted only in the basaltic lava flows (Deccan Trap formation) dominated area of Saurashtra, southern mainland Gujarat and north of Mumbai in Maharashtra (Rastogi et al., 2013; Sateesh et al., 2019; Sharma et al., 2020). Non-tectonic origin of earthquake swarms is suggested based on the fact that they occur only in trappean areas and do not correlate with any tectonic structure (Rastogi et al., 2013; Sateesh et al., 2019). However, seismic data available so far shows uneven distribution, with markedly dense clustering of earthquake shocks in the areas around Talala in the morphotectonic domain-II of present study area (Vanik et al., 2021). Studies carried out so far have pointed out that the swarms occur during the monsoon and extend for 4–5 months beyond it (Rastogi et al., 2013; Sateesh et al., 2019; Sharma et al., 2020). The close association of swarm activity with rainfall is well demonstrated in the region around Talala in SW Saurashtra and southern part of mainland Gujarat (Rastogi et al., 2013; Hainzl et al., 2015; Singh and Mishra 2015; Sateesh et al., 2019), though no linkage with geological zones of weakness could be established (Vanik et al., 2021). However, precise understanding of the phenomenon of widespread occurrence of earthquake swarm activity is a challenge as known and mapped geological discontinuities are few in Saurashtra.