# *Chapter - 2*

# REGIONAL STRUCTURE AND GEOLOGY

The Gujarat state in western India covers approximately 196,024 km$^2$ with ~1600 km long coastline. Gujarat state is divisible into three distinct zones based on seismicity, tectonics and geomorphology viz., Mainland Gujarat, Kachchh and Saurashtra (Merh, 1995). The Kachchh region is seismically active region to the northwestern part of Gujarat with several E-W trending master faults (Biswas, 1982, 1987). The mainland Gujarat is maximum covered by alluvial plains showing distinct geomorphic features reflecting various tectonic erosional and depositional landforms (Merh and Chamyal, 1997; Maurya et al., 2000). The Saurashtra horst also known as Kathiawar uplift, is a southwest tilted square shaped block between three coinciding rift basins viz., Kachchh at the north, Cambay at the east and Narmada at the south (Biswas, 1982, 1987, 2005; Bhattacharya and Subhramanyam, 1986; Gombos et al., 1995; Sethna et al., 2001; Chamyal et al., 2003; Rao and Tewari, 2005; Singh et al., 2013).

The Saurashtra peninsula is a distinct morphotectonic unit at the western continental margin of India. The major rivers flow outward radially in all directions from the central highland (Merh, 1995). It contains only Mesozoic and Cenozoic rocks ranging from Jurassic-Cretaceous to recent coastal deposits (Figure). It forms a rocky plateau bordered by Tertiary and Quaternary carbonate deposits with maximum part covered by trappean lava flows and associated dykes and plutons belonging to the Deccan Trap Formation (Merh, 1995). This semi-arid region is noticeable by uneven mounts and trap dykes that are prominently observed above the surrounding areas (Sant, 1999; Chamyal et al., 2003). It is restricted on all sides by Arabian Sea except the North-East part where it is flanked by alluvium plains of mainland Gujarat (Figure). The northeastern part of the region exposes Mesozoic sedimentary rocks of Jurassic period comprising Dhrangadhra-Wadhwan Formation which includes sandstones, conglomerates, shales and clays (Pappu and Marathe, 1977; Merh, 1995). The Deccan trap overlies the Mesozoic rocks and is occupied in the central part of the peninsula consisting of highly undulated and rugged hilly topography dissected by several rivers that flow out in all directions (Merh, 1995).

## 2.1 STRUCTURAL AND TECTONIC SETTING

The Saurashtra peninsular (covers the maximum part) also described as 'Saurashtra horst' or 'Kathiawar uplift' by Biswas (1987) is bounded by major faults from all the sides viz., North Kathiawar Fault (NKF) at the north, extension of West Coast Fault (WCF) at the west, extension of Narmada Son Fault (NSF) at the south and Western Cambay Basin Margin Fault (WCBMF) at the east. It is a quadrangular southwest tilted uplifted block surrounded by major rifts like Kachchh rift in the north, Cambay rift in the east and extension of Narmada rift to the south (Biswas, 1987). Three major Precambrian trends coincides in the Saurashtra region viz., Dharwar trend (NNW-SSE) in the southern part, Aravalli trend (NE-SW) in the northeastern part and Satpura trend (ENE-WSW) in the central part (Biswas, 1987).

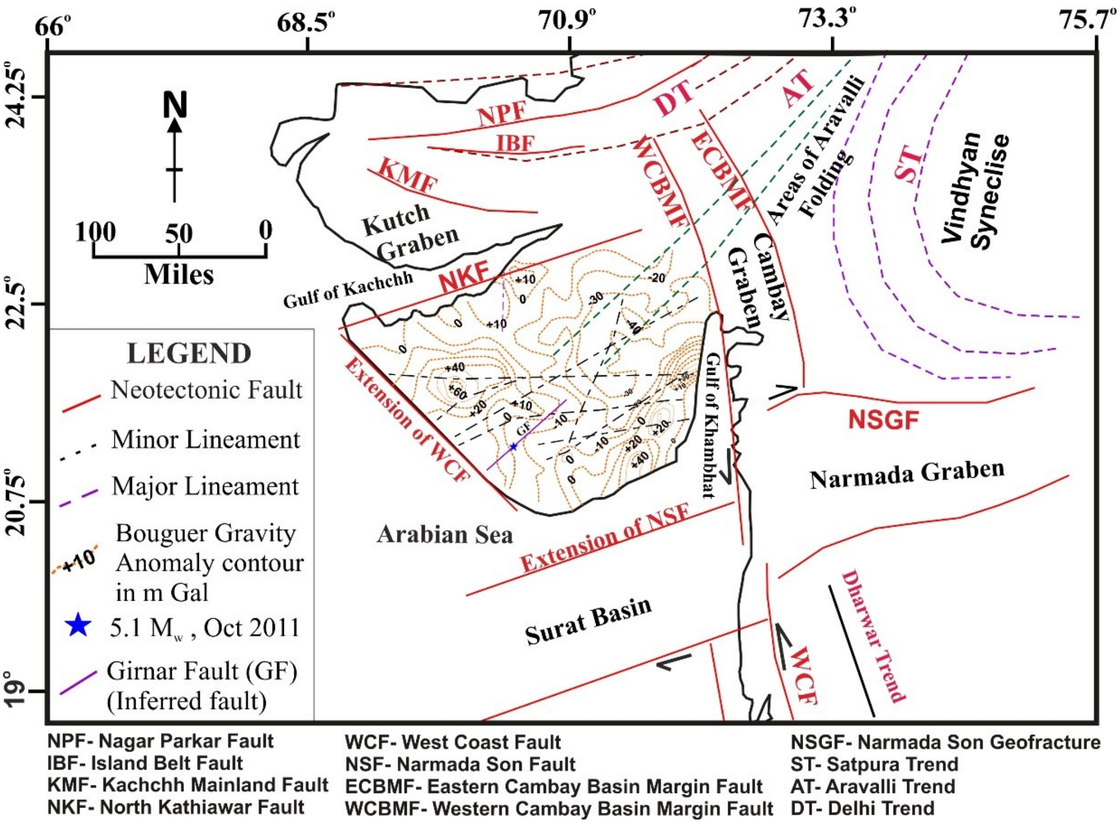


**Figure 2.1** Tectonic map of Saurashtra and surrounding region showing major faults, peri-cratonic rifts, Precambrian trends, structural lineaments and Bouguer anomaly contours (compiled by Vanik et al., 2018). Data included from Biswas (1987), Merh (1995), Dasgupta et al., (2000), Rastogi et al., (2013) and Bhattacharya et al., (2004).

### 2.1.1 Major Faults

The North Kathiawar Fault (NKF) is a ~ NE trending normal fault on the southern margin of the Kachchh basin and on the northern margin of Saurashtra horst passing from the Gulf of Kachchh (Biswas, 1987; Gowd et al., 1996). During Cretaceous-Paleocene, the Saurashtra block separated through frequent slips along the western extension of Great Boundary Fault (GBF) forming NKF (Biswas, 1987). Gowd et al., (1996) stated that the NKF formed during early Jurassic or earlier along with Kachchh basin and lower Narmada-Tapti valleys. There is a great significant of hydrocarbon exploration to the south of the NKF due to increase in sediment thickness because of southeastward tilt of the Kachchh basin towards Gulf of Kachchh (Paul et al., 2008). The extension of West Coast Fault (WCF) follows the straight western coastal belt of Saurashtra peninsula also known as Saurashtra Fault (Gowd et al., 1996), is a NW trending fault extended from N-S trending WCF in the western coastal margin of India (Biswas, 1987). The WCF is an important structural lineament, parallel to one of the major Precambrian Dharwar trend with its northward shift gave rise to Cambay graben (Biswas, 1987). The WCBMF (Bhattacharya et al., 2004) or 'West Cambay Fault' trending NNW-SSW marginal fault offsets by E-W trending Shihor Fault (SF) near Bhavnagar region. Both the faults transverse to each other is responsible for the swarm type of earthquake activity around Bhavnagar (Bhattacharya et al., 2004).

### 2.1.2 Major Rifts

Biswas (2005) mentioned that the horst lies between two parallel rift basins, the western offshore extension of Narmada rift and Kachchh rift. However, the Cambay graben to the east of the Saurashtra formed parallel to the Dharwar trend (Biswas, 1982) which is 2.3 Ga (estimated age of Dharwar trend) (Gombos et al., 1995). The horst is basically a large fault block that has settled between Kachchh graben at the north and Surat (Dahanu) depression at the south (Gombos et al., 1995). Several N-S to NNE-SSW trending lineaments detected in the western part of India paralleling the Cambay rift basin has evolved during late Cretaceous due to Reunion plume interaction with Indian lithosphere (Mishra et al., 2001). The East Cambay Basin Margin Fault (ECBMF) and West Cambay Basin Margin Fault (WCBMF) confines the Cambay graben (Vanik et al., 2018).

### 2.1.3 Precambrian Trends

The Dharwar trend is the oldest Precambrian basement grain trending north to NNW parallels the faulted Indian west coast along with series of extension faults (Biswas, 1987). He also stated that the western straight coastline as the faulted margin is due to the extension of West Coast Fault (WCF) along the Dharwarian trend extending northward that have caused the rifting between the Saurashtra horst and the peninsular shield. The straight western margin of the horst block is a faulted margin which follows the Dharwar trend and cuts across the Saurashtra arch uplifting this block (Biswas, 1987). The uplifted part of a WSW-plunging basement arch which divides the western continental margin into a northern Kutch-Saurashtra shelf and a southern Bombay- Kerala shelf. The arch forms the southern limit of the Jurassic sedimentation of the Indus shelf basin (Biswas, 1987). The Aravalli trend from the north cuts the

Cambay rift and enters the Saurashtra peninsular taking an acute eastward swing merging the Satpura trend (Rao & Tewari, 2005).

## 2.2 REGIONAL GEOLOGY & STRATIGRAPHY

Most part of Saurashtra shows rugged erosional topography comprising hills and ridges along with several volcano-plutonic complexes with varying composition and abundant dykes (Fedden, 1884; Mathur et al., 1926; Bose 1973; Melluso et al., 1995; Chatterjee and Bhattacharji, 2001, 2004; Sheth et al., 2011, 2012, 2013). At the coastal fringe, trap underlies Tertiary deposits and Quaternary sediments (Merh, 1995). The most extensive Quaternary deposits are the alluvial deposits along the east and southeast coast of the peninsula, where they are thought to be chiefly estuarine or marine, even though not fossiliferous (Gupta, 1972). The coastal tract of the region consisting erosional as well as depositional landforms comprises of sandy and/or rocky beaches, mudflats, sea caves, sea cliffs, notches etc. The available geological information (Table 2.1) on the stratigraphy of Saurashtra region based on (Pascoe, 1959; Chiplonkar and Borkar, 1975; Krishnan, 1982; Biswas, 1987; Aslam, 1987, 1992; Casshyap and Aslam, 1991, 1992; Merh, 1995; Khan and Ahmad, 1998; Khan et al., 2017) is summarized below.

### 2.2.1 Sedimentary Cretaceous Rocks

The northeastern part of Saurashtra is mainly occupied by Mesozoic rocks of Lower Cretaceous age overlying the Granite basement extensively exposed near Surendranagar, Dhrangadhra, Wadhwan and Rajkot (Merh, 1995). The deposition of Mesozoics lies unconformably over sub-surface Proterozoic basement comprises of granite. The stratigraphy shows the Cretaceous period distributed in two formations viz., Dhrangadhra Formation (older) and Wadhwan Formation (younger) (Merh, 1995).

**Dhrangadhra Group**

This group, later changed into older Mesozoic formation in Saurashtra, is dominantly sandstone covering extensively the northern Saurashtra (Merh, 1995). ~550 m thick sequence overlying Granite basement expected during borehole drilling near Dhanduka village (Alexander, 1979; Merh, 1995). Biswas (1987) predicted this formation to be the connected with the Wagad and Bhuj Sandstone. The coal and plant fossils found in this formation is suggestive of a coastal swamp and distinctive deltaic type environment which are linked with the Umia beds of Kachchh region (Merh, 1995). The age is from Upper Jurassic (Tithonian) to Lower Cretaceous (Neocomian and possibly extending up to the Albian) (Merh, 1995). The Dhrangadhra group was distinguished into four formations – Than, Surajdeval, Ranipat and Wadhwan Formation (Aslam, 1992, 1998; Khan and Ahmad, 1998; Casshyap and Aslam, 1991, 1992; Khan et al., 2017).

***Than Formation***

The oldest formation of the Dhrangadhra group, consisting of whitish to reddish sandstone, interbedded white shale or fireclay, siltstone and carbonaceous shale with thin coal bands (Casshyap and Aslam, 1992). These rocks were earlier identified as 'Than beds' (Pascoe, 1959) or 'Gondwana Beds' (Krishnan, 1982) of Kathiawar. It is ~125 m coarsening upward sequence and the depositional environment was backswamp of lower delta plain (Casshyap and Aslam, 1992; Khan, 2017).

***Surajdeval Formation***

The subsequent Surajdeval Formation of ~175 m sediment thickness comprising sandstone and conglomerate with interbedded red mudstone (Casshyap and Aslam, 1991; 1992). The formation shows recurrence of fining upward sequence with shoreline deposits affected by storm and tidal events (Khan et al., 2017) which was also reported during the deposition of this formation (Casshyap and Aslam, 1992).

***Ranipat Formation***

It consists of low lying areas with thin shale bands and cross-bedded channels and sediment thickness is ~200 m revealing fining upward sequence (Casshyap and Aslam, 1992). The depositional environment during the deposition of this formation was nearshore coastal, tidal and subtidal (Khan et al., 2017).

***Wadhwan Formation***

The Wadhwan Formation conformably covers the Ranipat Formation (Casshyap and Aslam, 1992) and the best exposure is found near Surendranagar (Merh, 1995). The formation name and initial mapping mainly consists of brick red calcareous sandstone with limestone bands (Fedden, 1884) and fossils comparable with bagh beds (Chiplonkar and Borkar, 1975). The mega shells of gastropods and pelecypods, bryozoans, echinoderms and microfossils are found suggestive of their shallow marine depositional environment (Merh, 1995). The rocks were also divided into three units – Kukda unit, Malechimata unit and Khamisana unit in ascending order (Casshyap and Aslam, 1992). Three members of this formation viz., Surendranagar Limestone Member, Navania Limestone Member and Bhaduka Limestone Member are connected with Nimar Sandstone, Nodular limestone and Coralline limestone respectively of Bagh beds of lower Narmada valley (Merh, 1995). However, Biswas (1987) has correlated this with the Bhuj Sandstone.

### 2.2.2 Deccan Trap Formation

The major portion of the Saurashtra peninsula is covered by Deccan Trap basalts and are considered to have been emplaced from fissures towards the end of the Mesozoic era (Merh, 1995). The traps are invariably jointed consists mostly of basaltic lava flows created due to hot mantle resulting in decompression melting brought from the plume to the lithosphere base (White and McKenzie, 1989). It is characterized by expansive, thick horizontal tabular sheets forming flat-topped hills with step-like terraces produced by differential weathering and erosion (Patro and Sarma, 2006). The traps cover majority of the peninsula with undulating plains dispersed by hills, ridges, intrusive and dykes (Merh, 1995).

***Trappean Lava flows***

These basaltic lava flows located as erosional conical and/or circular hill ridges displays altitude variations of several meters (Merh, 1995). The region shows volcano-plutonic complexes with varying composition and comprises of profuse rhyolite and granophyre (Fedden, 1884; Mathur et al., 1926; De and Bhattacharya, 1971; Rao, 1971; Bose 1973; Melluso et al., 1995; Chatterjee and Bhattacharji, 2001, 2004; Sheth et al., 2011, 2012) with abundant mafic dykes (Auden, 1949; Mishra, 1999; Sheth et al., 2013). A ~30 km long monzodolerite dyke in the central part of the region studied to understand its formation (Sethna et al., 2000). The samples of mafic lavas were studied in several towns and K-Ar method dating was done obtaining ages between 64 Ma and 67 Ma (Melluso et al., 1995; Chatterjee and Bhattacharji, 2001).

***Hills/Intrusive***

The Girnar hill, Barda hill, Alech hill and Osham hill in west and south Saurashtra whereas Chogat and Chamardi hill are in the eastern part of the peninsular. The Girnar hill, highest compared to others, is a large laccolithic intrusive that covers ~173.53 $km^2$ intruded in southern Saurashtra is characterized by rocks of basic and acidic composition (Mathur et al., 1926; Bose, 1971; Verma and Mittal, 1972; Pappu and Marathe, 1977; Paul et al., 1977). The intrusion postdates Deccan Trap time at 64.1 ± 1.4 my (Wellman and McElhinny, 1970). The mineralogical variation studied by Bose (1973) in the Girnar massif along with the chemical variation of the elements. However, the recent chronology ($^{40}Ar/^{39}Ar$) obtained by Sahoo et al., 2020 from lamprophyre dykes intruding Mount Girnar ages 65.9 to 66.1 Ma. The Barda, Alech and Osham hill to the west of the Girnar hill characterizes the laccolith intrusive and/or fissure type of igneous activity (Dave, 1971). The occurrences of these massifs shows high positive gravity anomalies of up to +70 mGal (Sethna, 2003). The geochronology of largest silicic complexes near Porbandar are Barda hill (dominantly granophyre) and Alech hill (rhyolites) shows 69.5 to 68.5 my (Cucciniello et al., 2019). The composition of Osham hill shows mainly rhyolite, pitchstone and basaltic andesite (Sheth et al., 2012). The Palitana flood basalt or lava sequence (~ 450 m) in the eastern part of the peninsular consists Mount Shatrunjay, Hastagiri hills and dykes which are associated with Dediapada-Nandurbar-Dhule dyke swarm (Sheth et al., 2013).

***Dyke swarms***

Countless prolific dykes are massive and resistant to erosion and form prominent positive relief in Saurashtra (Mishra, 2008; Dasgupta, 2018). The dyke swarms covered in few regions of Saurashtra has been studied by various workers to understand its formation and composition (Fedden, 1884; Auden, 1949; Subba Rao, 1971; Paul et al., 1977; Melluso et al., 1995; Chatterjee and Bhattacharji, 2001, 2004; Sheth et al., 2013; Cucciniello et al., 2015, 2019). In the eastern part of the region, the dyke swarms extending towards west mainly aligned to the major tectonic grains. These dyke swarms are associated with the Deccan volcanism cluster along E trending Narmada- Son-Tapti/Tapi belt (Mahadevan, 1994). These swarms mainly comprises of silicic and mafic dykes with andesite, rhyolite and granophyre rocks (Chatterjee and Bhattacharji, 2001, 2004; Cucciniello et al., 2020).

### 2.2.3 Laterites

The alteration of these trappean rocks resulting into bauxite and laterite deposits forming discontinuously between Tertiary rocks and Deccan Trap Formation from Jamnagar in the north up to Bhavnagar in the southeast (Merh, 1995). The favorable climate for lateralization prevailed when India passed over the equator after separating from Seychelles (Meshram and Randive, 2011). These Cretaceous trappean rocks crop out in the entire peninsula with small patches of Tertiary and Quaternary sediments at its fringes. The laterites and bauxites are widely observed in the northern Saurashtra region with no overlying of any younger deposits (Sychanthavong and Patel, 1987). The lowest sedimentary unit in N-S trending Cambay rift zone comprises of deposits of Lower Paleocene to Early Eocene age where the laterite layer marks as erosional unconformity (Sychanthavong and Patel, 1987).

### 2.2.4 Tertiary Rocks

The Tertiary rocks are mainly observed in the eastern, western and southern region of Saurashtra (Bhattacharya and Subramanyam, 1986). These sediments are buried and overlain by the Quaternary sediments near coastal zone of the Saurashtra region. Kaila et al., (1981) reported 400 m Tertiary layer under 1.3 km thick Deccan trap rocks on the Deep Seismic Sounding (DSS) profile along Navibandar-Amreli. The presence of these deposits also found in the offshore seismic refraction profile (Rao and Tewari, 2005). Due to Indian plate drifting towards northeast, the Tertiary deposits shows several structural attributes like folding mainly observed in the eastern Saurashtra (Singh et al., 2017). The Tertiary stratigraphy shows largely marine to fluvio-marine deposits (Merh, 1995). The lower Tertiary rocks from Paleocene to Oligocene age shows trappean and sub trappean rocks, lateritic rock formation and later unconformity.

The Eocene to early Miocene deposits are however covered by the later formations and are not exposed in the Saurashtra region. The offshore region has been studied by many workers and observed thin bands of Eocene and Oligocene rocks (Pandey et al., 2013; Singh et al., 2013). The patches of rocks and deposits of Early Miocene to Pliocene age are detected near the coastal areas of the peninsula (Merh, 1995). The rocks of Miocene age is highly fossiliferous in the peninsular (Mohan and Chatterji, 1956; Merh, 1995). The Miocene and Pliocene age comprises of Gaj Formation (Older) and Dwarka Formation (younger) (Merh, 1995).

***Gaj Formation***

The marine sediments deposited during Miocene period is covered extensively near the coastal areas of the Saurashtra peninsular (Merh, 1995). The sediments comprises of sandstone, limestone and conglomerate of Miocene and Pliocene age overlain by alluvium cover at few places (Merh, 1995). This formation is exposed from east to west coast and mostly noticed near Bhavnagar and Dwarka. Few isolated patches also observed in the southern and southwest coastal zone (Merh, 1995). The Gaj beds are almost horizontal and represents conglomerate, grits, sandstone, yellowish and bluish clays and marls (Merh, 1995).

The Gaj formation was divided into two units viz., Bhumbli conglomerate member (older) and Kuda sandstone member (younger) (Shrivastava, 1963). Later, the generalized stratigraphy of Cenozoic basin by Merh (1995) divides the formation in three units (lower to upper): Ratanpur Clay Member, Bhumbli Conglomerate Member and Kuda Sandstone Member. This was later modified by Bhatt (2003) into Ashapura Clay Member (lower unit) and Ranjitpur Limestone Member (upper unit) with the thickness of 90 and 5 m respectively. Piram beds are mainly observed in the eastern part of the Saurashtra which are also considered equivalent with younger Dwarka Formation (Merh, 1995). These beds cover the off-shore island of Piram near Ghogha area, Bhavnagar, conformably occupying the inter-tidal zone mainly indicating the fluvial and fluvio-littoral origin (Merh, 1995).

**Table 2.1** Stratigraphic framework of the Saurashtra region (after Merh, 1995, Bhatt, 2000, Sharma et al., 2017)

| Era | Period | Age | Group | Formation | Stratigraphic unit | Thickness (m) | Lithology |
|---|---|---|---|---|---|---|---|
| Cenozoic | Quaternary | Holocene | | | Unclassified Holocene deposits | | Beach and sand dunes, tidal clays, alluvium |
| UNCONFORMITY | | | | | | | |
| | | Pleistocene | Porbandar Group | Chaya Formation | Aramda Reef Member | 4 | Coral limestone |
| | | | | | Okha Shell Limestone Member | 10 | Off-white bioclastic limestone and conglomerate |
| | | | | Miliolite Formation | Adityana Member | 5 to 50 | White pelletoid limestone |
| | | | | | Dhobalia Talav Member | 8 to 10 | Alternating pelletoid limestone and micrite |
| UNCONFORMITY | | | | | | | |
| | Tertiary | Pliocene | | Dwarka Formation | | | |
| | | | | | Kalyanpur Limestone Member | 30 | Recrystallized fossiliferous limestone and sandy limestone |
| | | | | | Shankhodhar Sand-Clay Member | 60 | Sand clays and sandstones |
| | | Miocene | | | Positra Limestone bed | 25 | Bioclastic and coralline limestone with few dolomitic bands |
| | | | | | Piram Beds of SE Saurashtra | 9 | Conglomerate beds, silty sanstone, clay |
| | | | | | UNCONFORMITY | | |
| | | | | Gaj Formation | Kuda Sandstone member | 84 | Argillceous sandstone and sandly clay with calcareous layer |
| | | | | | Ranjitpur Limestone member | 5 | Yellow and brown fossiliferous limestone |
| | | | | | Bhumbli conglomerate member | 230 | Fossiliferous conglomerate, grit, argillaceous sandstone, minor clay content |
| | | | | | Ashapura clay member / Ratanpur clay member | 90 / 275 | Grey clay, variegated clays, marls with some gypsum bands / bluish grey gypseous clays with yellow limestone bed intercalation |
| UNCONFORMITY | | | | | | | |
| | | Oligocene | | | | | |
| | | Eocene | | | | 30 | Laterites |
| | | Paleocene | | Deccan Trap Formation | | 650 (+) | Basalt and other magmatic derivatives covered in places by laterite and bauxite |
| Mesozoic | Cretaceous | Late Cretaceous | Dhrangadhra group | | | 3 | Tuffaceous grit |
| | | | | Wadhwan Formation | | > 50 | Interbedded reddish, pebbly sandstone and mudstone |
| | | | | Ranipat Formation | | 200 | Sandstone interbedded with thin shale |
| | | Early Cretaceous | | Surajdeval Formation | | 175 | Lenticular sandstone bodies, conglomerate and interbedded red mudstone |
| | | | | Than Formation | | 125 | Grey sandstone, claystone, thick carbonaceous shale and coal |
| | Jurassic | Late Jurassic | | | | | |
| Proterozoic basement | | | | | | | |

***Dwarka Formation***

Dwarka Formation lies disconformably above Gaj Formation comprising sequence of highly recrystallized limestone and sandy clay, two distinct clastic dominated fossiliferous (Merh and Chamyal, 1993; Merh, 1995). The age of Dwarka Formation is upper Miocene to Pliocene and was also known as Dwarka Beds of Kathiawar (Biswas, 1971; Lele, 1973). The formation is divided into several stratigraphic units from older to younger such as Positra Limestone bed, Shankhodhar Sand-Clay Member and Kalyanpur Limestone Member (Bhatt, 2000). The lithology comprises of Conglomerate, siltstone, bioclastic, coralline and fossiliferous limestones, sandstones and sand clays (Bhatt, 2000; Sharma et al., 2017).

### 2.2.5 Quaternary sediments

The Quaternary period is divided into Pleistocene and Holocene (recent) age.

**Pleistocene deposits - Porbandar Group**

The Porbandar group of rocks is classified into two formations i.e., Miliolite Formation (Older) and Chaya Formation (younger) (Mathur et al., 1988; Bhatt, 2000, 2003).

***Miliolite Formation***

The 60 m thick sequence of Miliolite Formation lies unconformably over Dwarka Formation of Pliocene age (Mathur et al., 1988; Merh, 1995; Bhatt, 2000). The miliolite term has been given due to the presence of fossil Miliolidae, however, the miliolite rocks also comprises of allochems, pellets, molluscs, ooids and foraminifera (Biswas, 1971; Lele, 1973). This formation is classified into two members or stratigraphic unit viz., Dhobalia Talav Member (lower) and Adityana Member (upper) (Mathur et al., 1988; Bhatt, 2000). It mainly consists of Pelletoid (calcarenites) and fine-grained limestone (micrites) (Mathur et al., 1988; Bhatt, 2000, 2003).

The Quaternary carbonate deposits occurs in Saurashtra, Kachchh, Arabia and Sindh (Lele, 1973). These deposits, also known as 'miliolite limestone' or 'Porbandar limestone', were identified all along the western coastal zone with patchy outcrops in the central plateau region of Saurashtra and few places in Kachchh region (Biswas, 1971). However, the miliolites of Saurashtra is different from that of Kachchh identified by the clay minerals and detrital content analysis (Baskaran and Somayajulu, 1990). The origin of these bioclastic carbonate deposits, since many decades was in controversy, whether it is of marine or aeolian origin. Though, based on field studies, petrography and few other studies, the source and the depositional environment has been known. Gupta (1972) dated raised beaches and dead coral reefs suggesting sea level rise and not the uplift. However, in the southwestern coastal area, with the help of remote sensing methods, few strandlines or shorelines parallel to the coastline were detected by Baskaran et al., 1987. They used the $^{230}Th/^{234}U$ dating method of these strandlines and concluded tectonic instability and coastal uplift ranging 0.12 to 0.58 mm/year during Quaternary period. Several more samples collected of Quaternary deposits from the coastal regions for $^{230}Th/^{234}U$ and $^{14}C$ dating also favored coastal tectonics and uplifts (Baskaran et al., 1989).

***Chaya Formation***

The rocks in this formation consists of bioclastic and coralline limestone with conglomerate covering the middle to late Pleistocene age (Merh, 1995). These deposits are found to be ~15 m overlying the Miliolite Formation (Merh, 1995; Bhatt, 2000). This is divided into two members namely Okha Shell Limestone Member (lower unit) and Aramda Reef Member (upper unit) (Bhatt, 2000).

**Holocene deposits**

The Holocene deposits are mainly occupied in the coastal belt of the Saurashtra region from Bhavnagar in the east to Jamnagar in the west (Merh, 1995). These deposits mainly consists of beach deposits, sand dunes, mudflats and the alluvium (Merh, 1995; Bhatt, 2000). The intertidal flats are alternatively observed with the beach dunes and patches of alluvium mainly in the coastal area. The relict mudflats have been geochemical analyzed, studied and dated to know the paleoclimate and sea-level during mid-Holocene time (Banerji et al., 2015, 2016; Bhattacharya, 2020). Banerji et al., (2015) have reported ~1 m rise of the present sea level during that period as due to the coastal tectonics. However, the marine terraces and notches studied by Bhatt and Bhonde (2006) infers the southern coast shows sea level rise of 2 m above MSL during mid- Holocene. The climate was warm and humid around 4105 to 2640 year BP obtained from the sediment core study of the active mudflats near Diu Island (Banerji et al., 2017).

## 2.3 GEOPHYSICAL STUDIES

The Bouguer anomaly map of the Saurashtra peninsular by Mishra et al., (2004) shows numerous circular highs and lows of different magnitudes associated with these volcanic plugs. Chandrashekhar et al., (2002) outlined six circular highs with anomaly of 40 to 60 mGal in the southeast Saurashtra connected with the northeast oriented structural trend indicating deep seated faults or fracture zones. The magnetotelluric (MT) studies has also been carried out in the Deccan Volcanic Province (DVP) which revealed that the thickness of trap decreases from west to east (Patro and Sarma, 2009). The crustal structure of the Saurashtra region shows 3-4 km basement depth having more crust thickness in the northern part (42-44 km) than in southern region (36-46 km) (Chopra et al., 2014). In the eastern part of Saurashtra, between Palitana and Gulf of Cambay, large mafic dyke swarms crops out trending ENE-WSW (Sheth et al., 2013). The ENE trends in the eastern and southern part represents the Precambrian trend of Narmada-Son lineament (Mishra et al., 2001).

The magnetotelluric (MT) data shows sub-trappean Mesozoic sediments along with some faults and fractures (Sarma et al., 2004). Kaila et al., (1981) reported 400 m Tertiary layer under 1.3 km thick Deccan trap rocks on the Deep Seismic Sounding (DSS) profile along Navibandar-Amreli. The presence of these deposits also found in the offshore seismic refraction profile (Rao and Tewari, 2005). The depth of the basement is 3-4 km while the thickness of the crust is found to be more in the northern part (42-44 km) than in southern part (36-46 km) (Chopra et al., 2014). In the eastern part of Saurashtra, between Palitana and Gulf of Cambay, large mafic dyke swarms crops out trending ENE-WSW (Sheth et al., 2013) which represents the Precambrian trend of Narmada-Son lineament (Mishra et al., 2001). The *b*-value using earthquake catalogue studied by Singh et al., 2015 concludes that the seismic characteristics of Saurashtra horst tectonic block varies from that of the Kachchh basin.

The horst like structure formed at the south of Amreli in the south Saurashtra is due to the continuation ENE trending Narmada fault bounded on either sides (Sethna et al., 2001). All these fault system surrounding the square-shaped horst block remains tectonically active during late Quaternary (Chamyal et al., 2003; Merh, 1992; Pant and Juyal, 1993; Marathe, 1995). In fact, this region is affected by major tectonic events occurred after the breakup of Gondwanaland i.e., from middle to late Jurassic till late Cretaceous, that evolved rift basins, tectonic trends and numerous intrusions (Mishra et al., 2001).

Most prominent structures and features observed are the dense lineaments, dyke swarms, escarpments, volcanic plugs and denudation hills mostly in the trappean rocks (Merh, 1995). The lineaments observed south-west region are the Narmada-Son lineaments extending from eastern India up to Murray ridge at the west based on the geophysical, magnetic and bathymetric studies (Mishra, 1977; Bhattacharya and Subramanian, 1986). These abundant development of the features and ruptures displays irregular linear patterns and varying trends (Ramasamy, 1996) which are very well observed in the hilly terrains adjusts the drainage patterns (Hills, 1955).

**Table 2.2** Summary of geophysical and structural data generated by previous workers in Saurashtra (compiled by Vanik et al., 2021)

| Geophysical methods / structural data | Outcome /results | References |
|---|---|---|
| Deep Seismic Sounding (DSS) profile | 400 m Tertiary layer found under 1.3 km thick Deccan trap rocks along Navibandar-Amreli profile | Kaila et al., 1981 |
| Bouguer anomaly and gravity anomaly map | Dominant Precambrian trend of Narmada-Son lineament, west coast parallel trend related to coastal tectonics in Saurashtra | Mishra et al., 2001 |
| | High positive gravity anomalies up to +70 mGal and negative gravity anomaly in less dense areas | Sethna, 2003 |
| | Numerous circular highs and lows of different magnitudes associated with volcanic plugs | Mishra et al., 2004 |
| Bouguer anomaly and total intensity magnetic map | Six circular highs with anomaly of 40 to 60 mGal related with NE oriented structural trend indicating deep seated faults or fracture zones in SE Saurashtra | Chandrasekhar et al., 2002 |
| Magnetotelluric (MT) studies | Sub-trappean Mesozoic sediments along with some faults and fractures | Sarma et al., 2004 |
| | Thickness of trap decreases from west to east | Patro and Sarma, 2009 |
| Offshore seismic refraction profile | Crustal structure to the E Saurashtra indicates uplifted zone due to proposed fault | Rao and Tewari, 2005 |
| Petrography and mineral chemistry | Large mafic dyke swarms crops out trending ENE-WSW in E Saurashtra | Sheth et al., 2013 |
| Receiver function analysis | Basement depth (3-4 km), crust thickness more in the northern part (42-44 km) than in southern part (36-46 km) in Saurashtra | Chopra et al., 2014 |
| Fault-slip data and Paleostress analysis | E-W trending dyke swarm dominates the structural grain of the southern part which swings to NE-SW around Rajula | Vanik et al., 2018 |

## 2.4 EARTHQUAKE SWARM ACTIVITY

Gujarat state falls under seismic zones II, III. IV and V of the seismic zoning map of India considered as seismically prone intracontinental region (Yadav et al., 2008). Major tectonic domains of recurrent seismic activity in western India includes Kachchh, Narmada and Cambay rifts and Saurashtra. Kachchh is seismically active palaeorift basin (Biswas, 1987) with seismic zone V which has experienced several earthquakes of magnitude ≥ 6 in past and numerous moderate to low magnitude shocks till present. High magnitude earthquakes occur in Kachchh while moderate to low magnitude earthquakes have occurred in the Narmada rift (Chamyal et al., 2002; Raj et al., 2003; Mulchandani et al., 2007; Maurya et al., 2017; Joshi et al., 2013). The Cambay basin is characterized by low magnitude earthquakes that are few and are confined to the East Cambay Basin Margin Fault (Maurya et al., 1998; 2000).

The Saurashtra region, however, shows a different pattern of seismicity. The region is characterized by several phases of earthquake swarm activity over the last two centuries. It forms a vital geodynamic part of the western continental margin of India and falls under seismic zone III and IV of Seismic Zoning Map of India, Bureau of Indian Standards (BIS, 2002). The swarm earthquakes are mostly of low magnitude with few of moderate magnitude. Several places in the Saurashtra region, for example, Junagadh, Dwarka, Rajkot, Paliyad, Ghogha and Bhavnagar have a history of recurring earthquake activity (Bhattacharya et al., 2004; ISR report 08-09). The Talala region in the SW Saurashtra area of the Gujarat state of India is regarded as one of the seismically active areas, showing high rate of intraplate seismicity in recent years (Yadav et al., 2011; Rastogi et al., 2013; Singh et al., 2013, 2015). Apart from various studies on a regional scale, some researchers have attempted to look into the local structure and tectonics.

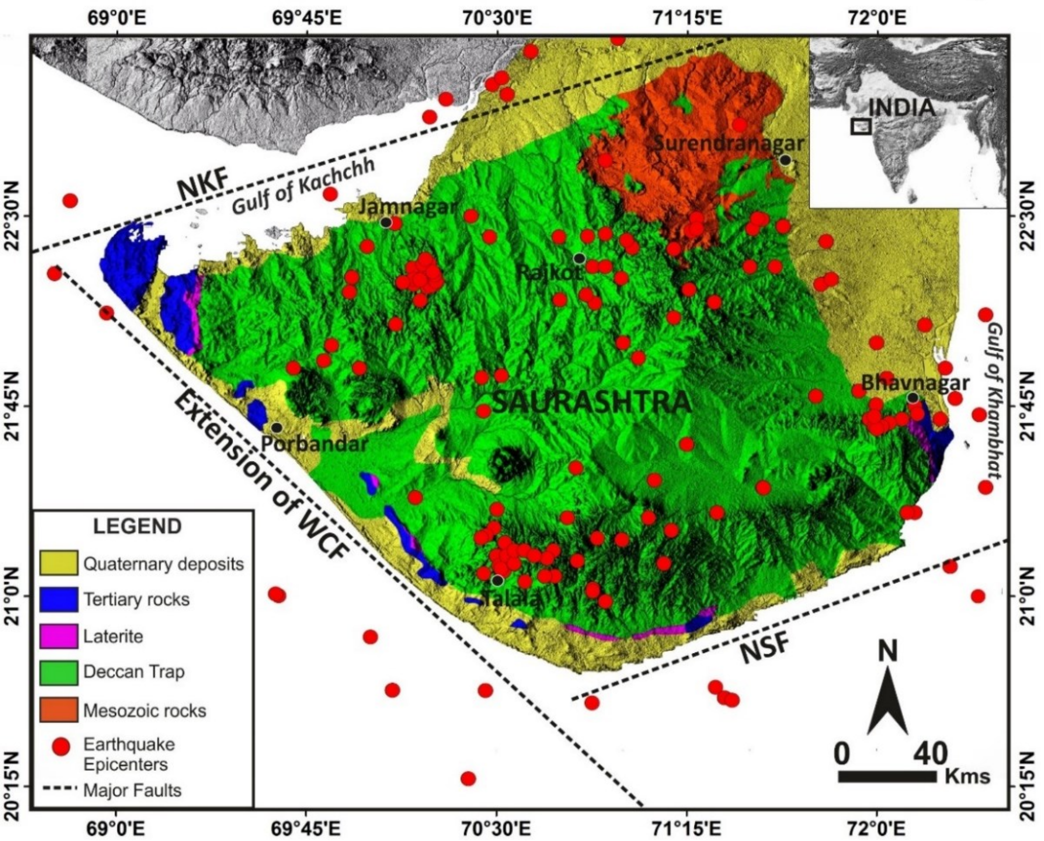


**Figure 2.2** Geological map of the Saurashtra peninsula draped over DEM with replotted epicenters (red dots) of earthquakes since 1872 till 2020 (after Vanik et al., 2021).

The swarm activity appear to be widespread in the region. Major concentrations of the epicenters are found to occur in the southern part, northern part and the eastern part. The most well-known areas include the area around Talala in southwest Saurashtra, Bhavnagar in the east and Jamnagar in the north where swarm type of earthquake activity of low to moderate magnitude has been recurrent since decades (Bhattacharya et al., 2004; Yadav et al., 2008, 2011; Singh and Mishra, 2015). From the earthquake catalogue of Saurashtra region from 1872 to 2016 (ISR, catalogue), the epicenters plotted on the map reveals swarm type of earthquake activity at few places. Junagadh region (SW Saurashtra) at the south has experienced a shock of 4.3 M, an offshore earthquake happened near Rajula with 5.0 M, an earthquake of 4.3 M has occurred in the region of Girnar Hills near Una and Bhavnagar region experienced a tremor of 3.6 M followed by nearly 132 aftershocks of 0.5 M to 3.8 M (Yadav et al., 2011). Swarm type of earthquake activities since 2001 is observed in Talala region of Saurashtra of magnitude 5.0 and less (Rastogi et al. 2013; Singh et al., 2013).

The region as a whole and the area around Bhavnagar, in particular, has been tectonically unstable (Bhattacharya et al., 2004). Between 9 August 2000 and 15 December 2000, there was a series of earthquakes of 0.5 to 3.8 magnitudes were recorded in Bhavnagar (Bhattacharya et al., 2004). The eastern part of the peninsular has also experienced magnitude 7 earthquake in year 1705, group of shocks near Paliyad in year 1938 from magnitude 5.0 to 6.0 (Rastogi et al., 2013). Other past records shows five earthquakes greater than magnitude 3, with a maximum magnitude of 3.8 (Bhattacharya et al., 2004; Yadav et al., 2011). In 2020, several low magnitude earthquakes occurred with one having magnitude >5 (*https://isr.gujarat.gov.in/latest-earthquakes-reports*). As several faults crosses the Bhavnagar area, several shocks are related with the offsetting of N-S trending WCBMF by E-W trending Sihor Fault (Bhattacharya et al., 2004). Beside Bhuj earthquake of January 2001, other earthquakes which have hit the region are Broach earthquake in 1970, Valsad earthquake 1986 and Bhavnagar earthquake in 1872 (Magnitude 5.0), 1919 (Magnitude 5.7), 1999 (Magnitude 2.5) and a recent earthquake in September 2000 (Magnitude 3.8) (Bhattacharya et al., 2004). However, all the previously recorded seismic data displays that Bhavnagar region is more active than other parts of peninsula (Bhattacharya et al., 2004).

The Jamnagar region has experienced swarm type of earthquake activity since last two centuries (Yadav et al., 2008). After 2006, more than twenty main shocks with long sequences of foreshocks and aftershocks have occurred along small faults at

Khankotda, Kalavad, Sanala, Moti Khavdi and Bhanvad areas in Jamnagar district (Rastogi et al., 2013). The North Kathiawar Fault (NKF) passing through the Gulf of Kachchh on the northern boundary of the region have shown low magnitude earthquake activity. Lalpur area experienced swarm with a magnitude maximum 2.5 event occurred around four villages near Sasoi Dam from early August up to the end of September 2003 (Rastogi et al., 2013). The area comprises of numerous dykes offsetting one another which can also be associated with low magnitude shocks (Yadav et al., 2011). However, the trend of aligned epicenter was NNW-SSE of earthquakes recorded during 2007 (Yadav et al., 2011). At a distance of 30 km south of Jamnagar, about 200 shocks with a main shock of $M \leq 4.0$, were felt near Khankotda village during September–October 2006 and about the same number was felt again between Vijrakhi and Khankotda during August–September, 2007 associated an $M = 3.2$ event (Yadav et al., 2011; Rastogi et al., 2013).