CHAPTER-2

GENERAL GEOLOGY

2.1 INTRODUCTION

The Gujarat state, westernmost part of India, covers approximately 1,90,000 km^2 area, and physiographically, it is divided into three distinct parts, 1. Mainland Gujarat, 2. Saurashtra, and 3. Kachchh. These are characterised by distinct geological formation and different age group of the rocks. The mainland Gujarat consist of Precambrian igneous, metamorphic and metasedimentary rocks; Mesozoic comprises igneous (Deccan Traps) and sedimentary and Cenozoic comprise of mainly sedimentary rocks. The Kachchh region consist of isolated patch of Precambrian (Meruda hill) rock, the predominant occurrence of the Mesozoic sedimentary with Deccan Traps and Cenozoic, mainly consist of marine and terrestrial sedimentary rocks (Biswas, 1999) with the latest lava flow (Deccan Traps) of Paleogene.

The Saurashtra Peninsula comprises relatively young geological formations (Fig.2.1) as compared to Mainland Gujarat and Kachchh. The Saurashtra Peninsula, is a rocky upland with rugged topography, primarily composed of igneous and sedimentary rocks belonging to the Mesozoic and Cenozoic Eras. The western and southern extremities of the peninsula are marked by Arabian sea, the northern fringe is marked by the Gulf of Kachchh and on the east lies the low-lying ancient sea connection between Gulf of Cambay and Kachchh (Merh, 1995). The peninsula hosts several geological formations, each with its own distinct lithology and age. At the base lies the Mesozoic sedimentary, approximately covered 5000 km^2, overlain by a thick sequence of tholeiitic and alkali basalt lava flows and higher peaks more than 300m of intrusive plutonic masses of the Deccan Traps, that were erupted during the Cretaceous-Paleogene time. The Deccan Traps are fringed on the coastal belt by sequence of sedimentary rocks of Paleogene, Neogene and Quaternary.

2.2PREVIOUS WORK

The geology of Saurashtra has been studied by many workers in different aspects due to their economic significance for mankind. The occurrence of the different rocks and minerals have attracted many geologists since the later part of the nineteenth century. Mesozoic rocks of Gujarat first attracted the attention of geologists towards the later part of nineteenth century.

Fedden (1884) is the pioneer worker who studied and described the Mesozoic geology of the old Kathiawar 'State' of Gujarat Pradesh and correlated the strata with the lower Narbada Valley of Gujarat. Then after many workers investigate the part of Saurashtra Peninsula on different aspects; the detailed account of the geology of Morvi and adjoining areas has given by Eunson (1892); the Mesozoic rocks of Saurashtra as 'Kathiawar beds' was described by (Oldham, 1871). Fox, (1931) has re-examined the geology of Saurashtra and discussed their age and correlation. Later, the economic importance was discussed by Dunn (1942) and gave an account of the occurrence of coal in the Mesozoic rocks, and mineral investigations in Saurashtra were carried out by (Taploo, 1942; Roy, 1953 and references therein). Many workers (Aslam, 1991; Satpal et al., 2006; Racey et al., 2016; Khan et al., 2017) have continuously refined and revised the Mesozoic stratigraphy of Saurashtra.

2.3 STRATIGRAPHY

The Saurashtra Peninsula encompasses the Cretaceous sediments, volcanic tuff, overlying the Precambrian-preceding crystalline bedrock (Singh et al., 1997). The exposed Mesozoic sedimentary mainly of Early Cretaceous age (Racey et al., 2016), are divided lithostratigraphically into Dhrangadhra Group and younger Wadhwan Formation (Racey et al., 2016).

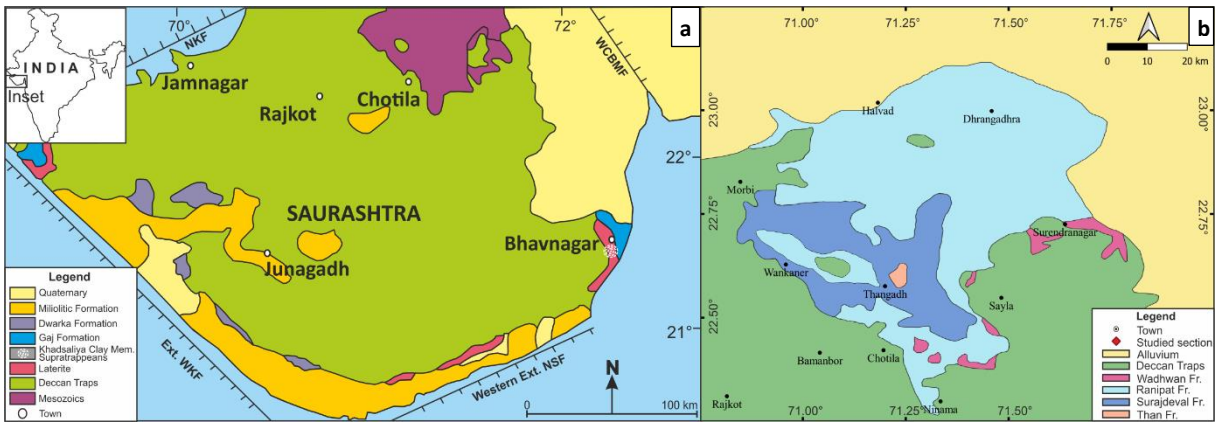

Fig. 2.1 a. General geological and structural map of the Saurashtra Peninsula. It is bounded by major faults (Western Cambay Margin Fault (WCBMF), Western Extension of Narmada Son Fault (NSF), Extension of Western Kathiawar Fault (WKF), Northern Kathiawar Fault (NKF)), b. Northern part of Saurashtra showing the Mesozoic units, Deccan Traps, and Intertrappean sites (modified after Biswas, 1969; Bhatt, 2000; Khan et al., 2017).

These rift sequences are widely covered by the Deccan traps of Cretaceous-Eocene, comprising volcanic-plutonic complexes of various compositions and form a rugged topography. The tableland also characterises some regional highs like, Chotila, Girnar-

Gokhnath, Barda, Alech, Osham etc. The Paleogene, Neogene and Quaternary sediments are found fringing the Deccan traps in the coastal zone (Bhatt, 2000) (Fig. 2.1a). The entire lithostratigraphy of the Saurashtra Peninsula is depicted in Table 2.1.

Age	Group/Formation	Members	Lithology
Quaternary	Mangarol		silty clays and argillaceous fossiliferous limestones
Neogene	Chhaya	Aramda reef	Coral reef limestones
		Okha Shell Limestone	Cream bioclastic limestones and conglomerates
	Miliolite		Lithified bioclastic limestone
	Dwarka	Kalyanpur Limestone	Recrystallised fossiliferous limestone and sandy limestones
		Shankhodhar Sand-Clay	Sandy clays and sandstones
		Positra Limestone	Bioclastic and coralline limestone with few dolomitic bands
	Gaj	Ranjitpur Limestone	Yellow, Brown Fossiliferous Limestone
		Ashapura Clay	Gypseous Grey clay, Variegated clays, marls
Paleogene	Khadsaliya Clay		Green to Greenish grey clays, Carbonaceous clay with Lignite
	Supratrappean		Lithomerge, Bentonite, Clays
Cretaceous to Paleogene	Deccan Traps With Intertrappean		Grey to dark grey and greenish grey to hard columnar basalts, vesicles filled with zeolite, quartz and calcite are also found Intertrappeans – Limestones, Chert, shales, clays, siltstones and sandstones occur between different flows as intertrappean beds
	Wadhwan	Bhaduka	Limestone

Cretaceous-Upper Jurassic?			Navania Limestone	Argillaceous limestone
			Surendranagar Sandstone	Tan-coloured massive, pebbly to fine-grained sandstones with intercalated marls
	Dhrangandhra	Ranipat		Light-coloured fine- to coarse-grained sandstones which are interbedded with thin shales
		Surajdeval		White to pale buff-coloured sandstones with local lenses of conglomerate and interbedded red brown siltstones
		Than		Planar and trough cross-bedded sandstones with coal beds
Basement (subsurface)				

Table. 2.1 Lithostratigraphy of the Saurashtra Peninsula (after Bhatt, 2000; Racey et al., 2016).

2.3.1 MESOZOIC STRATIGRAPHY

The Mesozoic rocks of Saurashtra are divided into Dhrangadhra Group and Wadhwan Formation. The rocks are exposed in the northern part of the peninsula, which unconformably overlay on the Precambrian basement and are uncomfortably overlain by Deccan volcanics.

2.3.1.1 Dhrangadhra Group

The oldest lithostratigraphic unit, Dhrangadhra Group, rests uncomfortably over the Proterozoic granitic basement (Singh et al., 2004). The sediments were deposited in Early Cretaceous (Hauterivian-Cenomanian) failed rift (Biswas, 1987), which are fluvial and transgressive shallow marine in nature (Khan and Ahmad, 1998; Racey et al., 2016; Khan et al., 2017). The group is divided into three formations, lower Than, middle Surajdeval and upper Ranipat, which are exposed as regional domal features in NE Saurashtra (Biswas, 1969, 1987). It is disconformably overlain by Wadhwan Formation of Upper Cretaceous.

2.3.1.1.1 Than Formation

The exposures of the formation occur around Thangadh village with maximum thickness of 120m. Major part of the formation is observed in well sections, exposed section

shows limited thickness and being of about 5-7 metres thick or even more (Racey et al., 2016). The sequence of this formation shows the coarsening upward, where sandstones is dominated by quartz arenite type which are medium to coarse grained with planar and trough cross-stratification. The quartz arenite is earthy white and reddish ferruginous, and their bed thickness increases in upward directions. Sandstone and siltstones which are horizontally laminated with occasional occurrence of ripples, cross-beddings and intercalated claystone containing plant debris. Shale and fire clays are grey and white respectively, while carbonaceous shale composed a thin lens of coal mostly observed in the lower part of the formation. The coal seams are usually thin, but more than three-meter thickness are observed in working mines. Many shale cores exhibit fragments of fossil plants. Varma and Rawat (1964) recorded the palynomorph assemblages, *Cyathadites* spp., *Osmundacidites wellmanii, Polypodiaceoisporites speciosus, Gleichenites* sp., *Trilobatus apiverrucatus, Lygodiumsporites* sp., *Acanthotriletes* sp., *Lycopodiumsporites* sp., *Callialasporites trilobatus, C. dampieri, Callialasporites* sp., *Cicatricosisporites cooksoni, Callispora* sp., *Ginkgocycadophytus deterius var. majus, Pityosporites* spp., *Podocarpidites* sp., *Classopollis pflugi, Classopollis* spp., *Monosulcites* sp., *Araucariacites* spp., *Granatricolpites* sp., *Granatriporites* sp. and *Punctatriporites* sp. The presence of angiosperm taxa *Granatricolpites* sp., *Punctatriporites* sp. and *Granatriporites* sp. suggests a Cretaceous age, whilst *Classopollis pflugi* is known from the Early Cretaceous and *Trilobatus apiverrucatus* also suggests Early Cretaceous (possibly Hauterivian) age (Varma and Rawat, 1964). A Late Barremian–Aptian age appears to be most likely for this assemblage.

The medium to coarse quartz arenite suggest deposition took place in meandering course of channels; horizontally laminated sandstone and siltstones with primary sedimentary structure and plant debris suggest a low energy delta-plain environment; carbonaceous siltstones and claystone with discontinuous coal seams associated with plant fragments interpreted to be deposited in back-swamp or interdistributary bays (Racey et al., 2016). The deposits of Than Formation suggests a prograding delta distributary complex (Aslam, 1991; Casshyap and Aslam, 1992; Khan et al., 2017).

2.3.1.1.2 Surajdeval Formation

The formation is dominated by trough cross-bedded medium to coarse grained sandstones dominated by quartz arenites, with lenses of conglomerate and interbedded laminated siltstones, with an overall fining-upward sequence of ~170 m thick. The lower part

consists of red friable mudstone followed by white and pink sandstone, with occasional thin lenses or white and grey shale, sandstone is stand out as ridges or conical hillocks. Lenses of pebbly conglomerate with pebble of about 2-6 cm in diameter sometimes occur in the upper part of the formation intercalated with coarse grained sandstone. There are 10 to 30 cm thick number of lenses of white and grey shale in sandstone. Red splintery mudstone is conspicuous because of its maroon colour, which is mainly exposed in the low-lying flat ground. The sediment characteristics of the formation suggest it is deposited in a distant delta-plain and coastal nearshore tidal setting, and it consists mostly of delta distributary channels (Casshyap and Aslam, 1992).

2.3.1.1.3 Ranipat Formation

The lower contact of the Ranipat Formation is gradational with Surajdeval Formation and is disconformably overlain by the Wadhwan Formation and in further north it is covered by a thick soil and alluvium of Quaternary. The formation is a 200m thick sequence of fine- to coarse-grained, cross-bedded and trough cross-bedded sandstones dominated by quartz arenites characterise by the bi-directional ripples, herringbone cross-bedding, and bioturbational structures. These are interbedded with thin shales and layered into fining-upwards cycles with thicknesses of up to 10m. Sandstone is mainly white, earthy, yellowish to pinkish in colour and fine- to coarse-grained in character. It forms characteristically the low-lying hills and ridges all around due to greater resistance to weather and erosion. Aslam (1991) reported a variety of trace fossils from this formation, including *Ophiomorpha, Planolites, Skolithos,* and *Thalassinoides.* The overall depositional environment is nearshore coastal, from beach through tidal/intertidal to subtidal (Racey et al., 2016).

2.3.1.2 Wadhwan Formation

Brick red calcareous sandstone with occasional thin bands of limestone was named as the Wadhwan Sandstone by (Fedden, 1884) after the town of Wadhwan. The formation is divided into three members, lower Suredranagar Sandstone, middle Navania Limestone and upper Bhaduka Limestone (Akhtar et al., 1996; Racey et al., 2016).

2.3.1.2.1 Surendranagar Sandstone Member

This member is composed of pebbly - fine-grained sandstones with intercalated marls and measures 5- 20 m in thickness. It is rich in fossils of mollusks, echinoids, and bryozoans, and calcareous algae. Borkar and Chiplonkar (1967), reported ammonites from this member and rests with angular unconformity? on the underlying Dhrangadhra Group near Kukda. The

macrofauna of the Suredranagar Sandstone Member indicates that it was deposited in a shallow-water, open-marine, normal salinity environment.

2.3.1.2.2 Navania Limestone Member

The Navania Limestone ember is an argillaceous limestone rich in echinoid fossils including *Hemiaster* and oysters like *Phygraea*. The depositional environment likely a deep shelf or lagoon. The occurrence of *Hemiaster* in beds, which is also found in the Bagh Group of Narmada's Nodular Limestone and Coralline Limestone formations, dates this to be a Turonian epoch (Racey et al., 2016).

2.3.1.2.3 Bhaduka Limestone Member

The Bhaduka Limestone, is a 5-20m thick limestone, with macrofauna like that of the Narmada's Coralline Limestone Formation, including bryozoa (dominated by *Chiplonkarina*), echinoderms (six species common to both Narmada and Saurashtra), and a comparable molluscan fauna. Among the echinoids, *Hemiaster subsimilis* is noteworthy for age dating because Smith and Wright (2008) discovered it in the Narmada Coralline Limestone Formation and is known from the Late Turonian of Madagascar. Ammonites have also been discovered, including *Placenticeras*, which is found in the Narmada Nodular Limestone (Bardhan et al., 2002; Kumar et al., 2018). Oysters are common towards the top of the member. Based on the macrofauna found, the depositional environment is interpreted as a shallow-marine shelf. The macrofauna is identical to that of the Upper Turonian Coralline Limestone Formation from Narmada (Racey et al., 2016).

The palynological investigation of the samples taken from the formation at depths ranging from 1490 to 1535 m in the Lodhika-1 well to the west of the studied outcrops yielded a palynomorph flora that included *Classopollis classoides* and *Perinipollenites elatoides*, which is similar to that found in Rajasthan's Parh and Upper Goru formations suggest a broad Late Jurassic-Neocomian age, whilst macrofauna is similar to the upper section of the Nimar Sandstone of Bagh Group, whereas the Aptian-Barremian age of the underlying Than Formation suggests a post-Aptian epoch (Racey et al., 2016; Behera et al., 2021; Shitole et al., 2021).

2.3.2 DECCAN TRAP FORMATION

The Deccan Traps are a major volcanic province in India created by a succession of volcanic eruptions initiated in Late Cretaceous. The volcanic activity resulted in huge lava

eruptions that covered large parts of the central and western part of India. They are made up of alternating basaltic flows at times with intervening sedimentary deposition known as intertrappean beds. They cover major portion of Saurashtra Peninsula, which unconformably overlies the Wadhwan Formation of Mesozoic sedimentary and are overlain and fringed by Paleogene, Neogene and Quaternary sediments along the coastal plains of Saurashtra (Merh, 1995). The traps form the elevated tablelands, plateaus, hills and ridges and are in the form of trap flows, intrusive, sills and dykes. It covers major part of the Saurashtra Peninsula and occur throughout the entire western shore. The formation contains effusive grey to dark grey and greenish grey to hard columnar basalts. Vesicles containing zeolite, quartz, and calcite can also be discovered in some locations. Certain clastic beds of shales, clays, siltstones, and sandstones occur locally as intertrappean beds that are poorly fissile between various flows. Its thickness ranges from 100m to 2000 m in the onland section (Singh et al., 2004; Satpal et al., 2006). These include several volcano-plutonic complexes, and a vast range of rock types from picrites through lamprophyres to rhyolites (Fedden, 1884; Chatterjee and Bhattacharji, 2001; Chandrasekhar et al., 2002; Tewari et al., 2009; Rao et al., 2015; Cucciniello et al., 2020; Sheth et al., 2022). Mafic dykes are abundant (Auden, 1949; Krishnamacharlu, 1972; Misra, 1999). Wells drilled for groundwater at Dhandhuka, Wadhwan, and Botad in NE Saurashtra encountered intercalated basaltic and picritic flows and minor pyroclastic rocks with a total thickness of~400 m, and the picrites have been interpreted as primitive liquids with 15–16 wt.% MgO (West, 1958; Krishnamurthy and Cox, 1977; Peng and Mahoney, 1995; Melluso et al., 1995, 2006, 2010 and Krishnamurthy et al., 2000).

West, (1959) described 48 flows from the boreholes in north-eastern Saurashtra.

Kaila et al., (1981) estimated the thickness of the Deccan Trap Formation in the west of Junagadh to be between 900-1300m and as low as 350m in the east. The Barda hills, located to the northeast of Porbandar, are composed of acidic igneous rocks. A 10 km diameter granophyre and rhyolite plug with a subvertical inward dipping flow structure indicating a volcanic vent is also visible in the Barda hills. Alech hills are dominated by magmatic rocks such as rhyolite and felsite, as well as some dolerite. Osham, located northwest of Junagadh, has trachy-felsite with pitchstone flow at the base. The Girnar hills are the most prominent feature of the Deccan Trap. This massif is composed of monzonite and diorite that occurs within a ring-dyke of granophyre in the central core or plug. The olivine gabbro also contains veins and dykelets of limburgite, nepheline syenite, monchiquite, and camptonite.

Sukheswala (1981) provided a detailed description of the variations in Girnar Hill's rocks. Basalt dykes can be found in the ENE-WSW, E-W, and NW-SE directions. They are 2 to 5 meters wide and extend for many kilometers. These are structurally regulated and have prominent fracture and lineament tendencies. Previously, NE-SW trending dykes were thought to be dyke clusters, but Misra (1981) discovered that they are fault controlled slanted flow and considered them to be an extension of the Narmada rift zone.

Melluso et al. (1995) sampled mafic lavas (as well as differentiated rocks) over a large area of Saurashtra (roughly bounded by the towns of Rajkot, Junagadh, Rajula, Amreli, and Shihor, (Fig. 2.1b) and discussed their mantle sources and magmatic evolution. Chatterjee and Bhattacharji (2001) studied mafic and silicic rocks from the Shihor-Palitana- Rajula area of eastern Saurashtra and inferred that the rhyolitic rocks had been derived by crustal melting and also dated a few Palitana flow samples by the K-Ar method and obtained ages between 64 and 67 Ma. Sethna and Ravivarma (2005), analyses major and trace elements of some Palitana basalt flows, and several of their analyzed samples show low MgO, TiO_2, and Nb contents.

Maithani et al. (1996) have presented some major and trace elements (including rare earth elements) data on the Osham rhyolites. The Saurashtra Decan Traps are abundant of silicic rocks (rhyolites and granophyres), especially in the Osham Hill, western Saurashtra exposes a small but significant sequence of rhyolite, pitchstone, and basaltic andesite lava flows (Cucciniello et al., 2015). The features like entablature tiers with irregular, chevron, rosette and skeleton jointing, and abundant glass and quench plagioclase and Fe–Ti oxides require convective cooling, by extensive interaction with meteoric waters, not only for the sheet lobes solidifying on the surface but even for dykes solidifying at depth (Sheth et al., 2022).

The Deccan Traps of Saurashtra also characterise with interspersed sedimentary deposits and alternating basaltic flows. The formation, which is made up of effusive grey to dark grey and greenish grey to hard columnar basalts, discordantly overlies the Wadhwan Formation (Merh, 1995). Vesicles including zeolite, quartz, and calcite are seen in some areas. Some locally occurring, weakly fissile clastic strata of siltstones, sandstones, and clay/shale exist between various flows.

2.3.2.1 Intertrappean

Intertrappean beds are sedimentary deposits occurred between two Deccan Trap lava flows marks the intermittent events of intrusive. The intertrappeans of Saurashtra are studied by many workers (Fedden, 1884; Borkar, 1973, 1975, 1984, 1986; Shringarpure, 1985; Arratia

et al., 2004; Samant et al., 2014) and they found vertebrates, invertebrates and palynofossils. It mainly comprises of fine clastic sediments including shales with subordinate amount of sandstones, limestones and chert deposited in lakes, and other bodies of water that existed between the lava flows. Recently, Patel and Shah (2023) have studied the Saurashtra Peninsula intertrappeans and logged in details. Their exposures are found in patchy form and denuded; their occurrences are observed on surface as well as in subsurface (dug wells). The maximum thickness is 35 meters observed near Ninama village. It mainly consists of fine grained clastics such as shales, siltstone, mudstone, clatystone, mudshales with bivalve bearing fine grained sandstone; and chemically formed rocks includes limestones and cherts. It is found to observed near Bamanbor, Ninama, Chotila, Garida, Motamatra, Rangpar villages etc. These intertrappean beds are highly fossiliferous in nature and mainly consist of organic wall palynomorhs that are useful in dating gave rise Paleocene to Lower Eocene (Patel and Shah, 2023). Detailed lithostratigraphy of the intertrappean succession of them Saurashtra Peninsula is described in chapter 4.

2.3.3 CENOZOIC STRATIGRAPHY

Saurashtra Peninsula comprises Paleogene, Neogene and Quaternary succession all along the coastal tracks. The Paleogene succession is considered as supratrappean, occur as subcrop, but exposed along the eastern coast in bay of Khambhat due to extensive lignite mining. It is known as supratrappean and above sequence named as Khadsaliya Clay Formation (Bhatt, 2000; Thakur et al., 2010). Neogene and Quaternary sequence are lithostratigraphycally divided into Gaj Formation, Dwaraka Formation, Miliolite Formation, Chhaya Formation and Holocene deposits (Bhatt, 2000).

2.3.3.1 Supratrappean

The supratrappean succession is rest nonconformable over the Deccan traps, usually occur as subcrop and exposed in lignite open cast mining area due to intensive excavation. It mainly consists of lithomerge, bentonite, clay and reworked bentonite. The supratrappean is rest unconformable over Khadsaliya Clay Formation of Eocene age has assigned Paleocene to Lower Eocene? age considering its stratigraphic position.

2.3.3.2 Khadsaliya Clay Formation

This formation is not exposed on surface, but a well-developed sequence observed in working lignite mines in the Bhavanagar District. This formation comprises brownish black fine-grained lignite associated with fine grained greyish white clay and greenish grey shale

overlying the supratrappean (Lower Eocene) and Deccan Traps (Cretaceous-Eocene) holds the lignite deposits together with carbonaceous clay. This clay is soft, fine grained and sticky in nature and equivalent to Cambay Formation (Thakur et al., 2010; Singh et al., 2017). Lignite seams unconformably lie on the weathered trap on lithomargic clay. They become deeper towards east to northeast and diminish towards sea. The seams show an average gradient of 5-10° dip towards center of the basin. The lignite seams are brownish black, fine grained and amorphous and tend to develop cracks when exposed to air. The lignite seams contain specks of resin, pyrite and iron nodules in abundance that can be picked by hand. Based on palynofossils age of this formation is assigned as Eocene (Monga et al., 2015; Singh et al., 2017).

2.3.3.3 Gaj Formation

Gaj Formation is exposed on the western margin of the Okha Rann and attained thickness of about 30 to 40m. It occupies 300 sq. km. in Jamnagar and Devbhumi Dwarka districts. It is dominated by clays, gypsum, calcareous silt, siltstone and thin bands of limestone (Bhatt, 2000). They are mostly argillaceous and partially calcareous. Bhatt (2000), classified Gaj Formation into the Ashapura Clay and Ranjitpur Limestone members.

2.3.3.4.1 Ashapura Clay Member

The Ashapura Clay Member is mostly made up of laminated clays of yellow, maroon, and grey colour. This member's topmost unit is made up of silt marl and siltstone. It occurs as narrow bands of fossiliferous material at various depths, where most of the molluscan shells are dissolved and replaced by mineral matters leaving their impressions in the form of mould and cast, respectively, that are easily discernible from the original material of the shells. The distinctive earthy yellow clays of Okha Rann's eastern region are unconformably layered atop laterites with a horizon of bouldery conglomerate at the base and gravelly material a meter thick at the top. The unit consists of typical yellow fossiliferous limestones which include mainly mollscan mega fossils, *Turitella, Natica, Cerithium, Cypraea, Conus, Ostrea, Acila, Arca* and *Venu*s (Bhatt, 2000).

2.3.3.4.2 Ranjitpur Limestone Member

The Ranjitpur Limestone Member of lower Miocene, overlying the Ashapura Clay Member, is a thin, calcareous unit, about 5m thick, comprising of yellow to brown colored compact fossiliferous limestone. The limestone shows cross bedding, with *Acila, Arca, Pecten,*

Ostrea and corals (Bhatt, 2000). The presence of *Pectunculus pecten, Pecten* sp. *Pecten bouei, Pecten favrei* and *Ostrea multicostata* and large foraminifers belonging to Miogypsinidae, are attributed to a Lower Miocene age.

2.3.3.4 Dwarka Formation

The Dwarka Formation disconformably lies over the Gaj Formation and is made up of recrystallized limestone and sandy clay layers with a thickness of 110 m. The two main fossiliferous sequences that make up most of the formation are interspersed by clastic-dominated unfossiliferous beds (Bhatt, 2000). It is further divided into Positra Limestone Member, Shankhodhar Sand-Clay Member, and Kalyanpur Limestone Member (Bhatt, 2000).

2.3.3.4.1 Positra Limestone Member

The coralline and fossiliferous limestones of Positra Limestone Member lay disconformably over the Gaj Formation. This member at times exhibits ripple and trough cross beddings. Corals like *Flabellum* sp*., Stylophora* sp. and *Orbicella conoidea* are reported from this member. This unit can reach a maximum subsurface thickness of roughly 25metres. Based on fossils, a Lower Miocene age is assigned for Positra Limestone Member (Bhatt, 2000).

2.3.3.4.2 Shankhodar Sand-Clay Member

The Shankhodhar Sand-Clay Member is best exposed at Bet Shankhodhar (Bet Dwarka), characterised by a 12m thick grey-yellow clay, with bands of sandy clays and greyish white consolidated sands. Fossil evidence is recorded as casts and moulds. It also exhibits low angle cross bedding, ripple drift lamination and ripple marks with burrow tubes, fecal pellet mounds and animal trails. Towards the top of the member, thin alternate sand and clay layers are characteristic with highly recrystallized yellow limestone (Bhatt, 2000).

2.3.3.4.3 Kalyanpur Limestone Member

The Kalyanpur Limestone Member is a recrystallized pink to brown fossiliferous limestone that forms an abrupt contact with the non-calcareous clastic-dominated sequence underneath. The rocks exhibit planar and trough cross-beddings. The uppermost portion of Dwarka Formation is characterized by this Member, which is widespread and present throughout western Saurashtra coastline. It is possible that the Member is a younger litho-unit given that it has a clear unconformable contact with the sand-clay phases of the other half of the Dwarka Formation. Based on *Pecten pascoei*, a lower Pliocene age is defined for this member (Bhatt, 2000).

Recently, Kundal and Mude, (2009), Kundal et al., (2016) and Mude et al., (2021) have provided systematic descriptions in detail for the number of calcareous algae from the Neogene-Quaternary succession of the Saurashtra Peninsula.

2.3.3.5 Milliolite Formation

The Milliolite Formation marks the beginning of Saurashtra's Quaternary geological record of Pliestocene age (Merh, 1995; Bhatt, 2000), spread over southern and south-western coastline of Saurashtra and patchy occurrence in the central Saurashtra. The formation is mostly cemented by low magnesian non-ferron sparry calcite cement and is made up of medium to fine grained, finely sorted, rounded to subrounded allochems such foraminiferal tests, peloids, molluscan shell fragments, coral, bryozoan, echinoderm, etc. (Bhatt and Patel, 1998). Depending on the paleogeography of the pre-miliolite, it exhibits a wide range of thickness. Its aeolian deposition has been assumed based on the high angle tabular and wedge type planar cross stratifications, as well as the mound-like body shape (Biswas, 1969). Its maritime deposition has been supported by the composition, which is mostly bioclastic (Lele, 1973). Recent theories acknowledge the existence of both marine and aeolian miliolites. Merh (1980) and Bhatt (2003) have both analysed the specifics of this formation. This formation is divided into two members, the lower Dhobalia Talav Member, which is composed of pelletoid limestone and micrite in alternate layers. The upper Adityana Member, which is composed of pelletoid limestone 'calcarenite' with a white tint.

2.3.3.6 Chaya Formation

The Chaya Formation was officially recognized as a litho-stratigraphic unit by Mathur and Mehra (1975) and refers to the coarse-grained bioclastic limestone deposits that are present in association with Milliolitic limestone in the coastal region of western Saurashtra. It comprises of 'calcirudite' rocks, which are described as buff-colored, coarse-grained, slightly seaward sloping rocks studded with megafossils. It is divided into lower Okha Shell Limestone Member and upper Aramda Reef Members.

2.3.3.6.1 Okha Shell Limestone Member

The Okha Shell Limestone Member, is off-white in coloured, medium to coarse grained highly fossiliferous porous limestone, with planar and trough cross bedding, rich in molluscan shell fragments and bioclasts. Earlier Holocene age was assigned to this member by Mathur et al. (1988) is subsequently revised and assigned Middle to Late Pleistocene age by Bhatt and Patel (1998).

2.3.3.6.2 Aramda Reef Member

The Aramda Reef Member, which is composed of coralline limestone well exposed near the village of Aramda. The corals belong to the order Scleractina and Hexacorallia, charactering a barrier type of coral reef. Gupta (1972) suggested 4575+105 years using C^{14}, while Gupta and Amin (1974) suggested 34 to 123 kilo years using $^{230}Th/^{234}U$ method. Somayajulu et al., (1985) suggested an age bracket of 118-176 kilo years.

2.3.3.7 Holocene Deposits

Saurashtra's Holocene record has not yet been thoroughly studied. It may be utilized to reconstruct the region's Holocene past because of its stabilized coastal dunes, beach sands, elevated mud flats, shell beds, dead coral reefs, etc. Other than these, the Holocene deposits which are not classified include fresh water river deposits, pediment debris, beach and tidal clay deposits, etc.

2.4 STRUCTURES, TECTONICS AND BASIN EVOLUTION

The majority of the Indian Peninsula is characterised by shields, with intracratonic and pericratonic fault-bounded basins (Biswas, 1987). It exposes Archaean gneisses, schists, Precambrian sediments and igneous rocks metamorphosed to various degrees along with covered volcanic flows of Deccan and Rajmahal, Late Precambrian-Early Palaeozoic sediments, Gondwana rocks (Biswas, 1987). The Precambrian orogenic trends, the NNW-SSE Dharwar trend, the NE-SW Aravalli trend, and the ENE-WSE Satpura trend, dominates the structural configuration of western India (Biswas, 1987). Between the three intersecting rifts (Kachchh, Narmada, Cambay), the Saurashtra horst still exists as a plunged block along the major Precambrian trends. It is a roughly square-shaped block with a southwest tilt. The Dharwar trend is followed by its straight western boundary, which is also faulted. This block is elevated by the western margin fault, which runs through the Saurashtra arch (Biswas, 1987). The Saurashtra uplift is horst, bounded by faults on all sides, Western Margin Fault of Cambay towards east, Western extension of Narmada-Son Fault towards south, West Kathiwar Fault (West Coast Fault) towards West and North Kathiawar Fault towards North (Fig. 2.1a). It forms the southern limit of the Jurassic sedimentation of the Indus shelf basin (Biswas, 1987). During Early Cretaceous, it subsided along the Western Margin Fault of Cambay and formed an extensive depositional platform of thick deltaic sediments. During Late Cretaceous, a part was uplifted as horst which separated three graben basins, Kachchh Basin, Cambay Basin and Narmada Basin.

2.5 MINERAL WEALTH

The Saurashtra Peninsula is rich in minerals and building materials like abauxite, bentonite, sandstone, basalt, limestone, calcite, chalk, coal, diatomaceous earth, fire clay, glass sand, gold, gypsum, lignite, etc. The occurrences of the economic minerals are described as follows based on Gupta et al. (2012).

2.5.1 AGATE:

Jamnagar: Occurrence of chalcedony, agate and jasper conglomerate, both in situ and as well as transported pebbles of varying sizes, has been reported from Veratiya and between Pardadhari and Latipur. Geodes containing Moss-agate and chalcedony are reported to occur near Badanpur, Bori, Jiwapur, Thoriali and Vijarkhi.

Junagadh: Milky-white chalcedony and agate as geodes have been reported along the southeastern border of Gir Forest near Khambha. The occurrence of pebbles of agate and chalcedony has also been noted in a nala between Hemal and Sokhra. A moss agate-bearing conglomerate has been noticed near Khijaria in Rajkot district. Agate pebbles have also been noticed near Lakhanka (Bhavnagar district).

2.5.2 BASE METAL:

Jamnagar: A six m thick basalt flow exposed in a well at Beh shows the presence of disseminated native copper. Specks of native copper are also reported from other nearby wells.

Junagadh - Banej Nes: The occurrence of lead-copper mineralization associated with quartz veins traversing Deccan Traps has been known since 1884. Hydrothermal galena and chalcopyrite mineralisation, in narrow quartz veins is noticed over a length of 340 m, within a fault breccia zone along a N-S trending fault. Mineralization is, however, sporadic in nature.

Rajkot - Bhayavadar : Presence of native copper has been recorded in Deccan Traps, three km SE of Bhayavadar. Dissemanations and thin plates of native copper are noticed, in abundance, in lava flow along joints, calcite veins and in zeolite fillings.

2.5.3 BAUXITE:

Jamnagar: Segregated pockets of bauxite are reported from 90 km long laterite belt, generally 20-40 km from the coast. The laterite rests over the Deccan Trap hillocks with an intervening layer of lithomarge or ferruginous clay. Major occurrences are located at Bankodi, Bhatia, Bhopalka, Gandhri, Havardi, Hadmatia, Lamba, Lol, Mewasa, Asota, Mahadevia, Nandana, Navadra, Ran, and Virpur.

Junagadh: Pockets of bauxite associated with laterite are located at Aditiyana, Babda, Bakharala, Baradiya, Beran, Chotilibili, Gosa, Palakhada, Matadi, Simani and Una.

Amreli: Bauxite occurrences associated with laterite are reported from Balanivav, Chelna, Hemal and Kagvadar.

Bhavnagar: Major bauxite occurrences are located near Longdi, Otha and Talagajarda.

2.5.4 BENTONITE:

Bhavnagar - Khadsaliya: A 10 in thick bentonite horizon in the Drod river section is observed near Khadsaliya. This is the thickest bentonite horizon recorded in the state. Bentonite is bluish to yellow in colour. A five meters thick bentonite sequence is exposed near Tagadi Budhel area in quarries sections. The upper two meters shows massive bentonite while the lower three meters section has bentonite with original igneous texture retained in the form of altered shards, remnants of crystals, glass, etc. indicating in situ weathering of igneous rocks. Other bentonite occurrences include thin and narrow, coastal fringe deposits near Adhewada, Akwada, Alapar, Badi, Bhuteswar, Chitra, Devaliya, Juna Ratanpur, Lakhanka, Malanka, Malpur Morchand, Padri, Padva, Rajpara, Sakhavadar and Thoradi.

Jamnagar: Deposits of bentonite associated with lateritic rocks overlie the Deccan Traps. Important occurrences are reported From Bhopalka, Jodiya, Mahadevia, Mewasa, Nandana and Ran.

2.5.5 BUILDING STONE:

Basalt: The places from where basalt is mined for building purposes from different places of Saurashtra region are Dhanduka, Shekhpur, Tatanpur and Umrala in the Dhandhuka taluka (Ahmedabad district); Amrapur, Amreli, Babrala, Bhura Khiya, Dhari, Kherali, Kotdapitha, Kunkavav, Lathi, Mota Mujassar, Rajula, Rampur and Wadia (Amreli district); Bhavnagar, Phulsar. Ramdhari, Savarkundla and Sihor (Bhavnagar district); Garudeshwar and Mori (Bharuch district); Beh, Hadiana, Jamnagar, Jasapur, Juvanpur, Khakharda, Khambhaliya, Kharva and Vachhu (Jamnagar district); Adwana, Junagadh, Keshod and Ranavav (Junagadh district); Bordi Samdhiara, Daldi, Dharampur, Gondal, Jetpur, Kotda/Sangani, Lakhdhirgarh, Mahindranagar, Navagan, Nyara, Panchvada, Rajkot, Vasavad, Vegadi, Virpur and Wankaner (Rajkot district).

Sandstone: The places from where the sandstone is mined for building purposes from different places of Saurashtra are Garia, Lunsar, Makansar, Malia, Morvi, Paneli, Ratidevli, Sajanpur, Sawadi, Sullanpur and Wankaner (Rajkot district), Chotila, Chuli, Dharangdhra,

Halvad, Jasapur, Jijuda, Khamisana, Kondh, Limbdi, Muli, Ramparda, Ratanpur, Samatpur, Sayala, Songadh, Thangadh, Umarda, Wadhwan and Waghela (Surendranagar district).

2.5.6 CALCITE:

Amreli: Near Ingorala, lenticular calcite veins are found to intrude the porphyritic basalts. Other important deposits are located near Babra, Bhurakhiya, Dhareswar, Jhikhiali, Kotda, Khakhabhai, Mota Agasia, Muljer, Nanudi and Sukhpar.

Jamnagar: Calcite deposits of the district are the best in India. There are many occurrences of calcite filled fissures and veins in the vesicular basalt. The veins commonly strike along NE-SW and NW-SE with steep dips. Major veins run over a distance of a few hundred meters to more than 3.5 km. The width of the veins reaches up to 1.5 inch. Calcite is white, red, pinkish grey and yellow in colour. At some places well developed crystal aggregates occur within the veins. Major vein deposits are located at Chandranga, Kalwad, Kalyanpur, Kenedy, Lalpur, Marpur, Navadra, Patelka, Pithadia, Sapar, Vanthli, and Virpur. Occurrence of calcite vein deposits up to six meters depth within the Deccan Traps have been reported from Adwana, Bhakharla, Bhatkari, Gadhagra, Maria and Ramgadh (Junagadh district). Minor occurrences of calcite associated with Deccan Traps are noticed near Moraiya, Morvi, Padadhari and Pithadia (Rajkot district).

2.5.7 CHALK:

Junagadh: The chalk deposit is associated with the miliolitic limestone of the Quaternary age. The chalk, overlain by a pisolitic limestone, laterally grades, at places, to pink or creamish miliolitic limestone, and is underlain by hard miliolitic limestone or earthy to greyish-green weathered trap. The chalk contains pebbles of limestone and foraminifers like *Rotalids, Quinquiloculina, Globigerina,* etc. There are four main chalk deposits in the area. Open cast mining is carried out by manual removal of the hard compact limestone overburden.

2.5.8 COAL:

Surendranagar: Coal seams of Upper Gondwana age have been reported from the Than Formation of the Dhrangadhra Group (Lower Cretaceous). The Than Formation consists of grey shale, carbonaceous clay with bands and lenses of coal. In the south of Khakhrathal, ~21 sq km area has been demarcated where 0.11-0.71 m thick one coal seam exists below 5-15 in thick overburden of sandstone and grey shale. Near Than village, about 2.61 sq km area has been delineated where a coal seam varying in thickness from 0.11-0.73 m occurs below a 7.25 m thick overburden of sandstone, grey shale and carbonaceous shale.

2.5.9 DIATOMACEOUS EARTH:

Bhavnagar: In Gogha taluka, a diatomite-like bed of about one-meter-thick rests unconformably over lateritic material and is overlain by clay beds. The diatomaceous bed appears to be discontinuous and is exposed at Padral, Morchand and Khadsaliya.

2.5.10 FIRECLAY:

Rajkot: Fireclay found associated with the Than Formation of the Dhrangadhra Group, is of very good quality and is locally used for ceramics. A five to six meters thick carbonaceous dark clay bed, underlying a four-meter-thick bed of reddish clay, occurs near Hasanpur. It is used for making refractory bricks. In Refaleswar quarries, a 1.2-1.5 m thick dark grey, carbonaceous clay bed is exposed below a 3.6 m thick bed of impure reddish clay. This fireclay is horizontally bedded and extends over an area of 1.2 sq km. In Ratidevli, a three- to five-meter-thick clay bed is reported below a three-meter-thick sandstone bed. In Udepur, a black, plastic, carbonaceous clay bed, 0.9-2.5 m in thickness, occurs below a two-meter-thick sandstone horizon. This clay bed containing carbonised leaf and stem impressions covers an area of about 5.0 sq km and occurs alternately, as lenses. Occurrences of fireclay beds are also reported from Adepar, Jambudia, Jodhpur, Lakhdirnagari, Makansari, Matel, Panchasya, Sultanpur, Vinaygadh and Wankaner.

Surendranagar: Occurrences of several clay beds associated with the rocks of the Dhrangadhra Group are known. The localities of important fireclay occurrences are Amarapur, Bagaleda, Dhrangadhra, Godhda, lshwariya, Khakhrathal, Palsa, Rampar, Ramparda, Sarla, Songadh, Talrvi, Than, Vagadia and Wadhwan. The clay beds vary in thickness from 0.511 m and are covered with Recent soils. The fireclay, grey or black in colour, has good plasticity and is widely used for manufacture of pottery, tiles and stone ware pipes.

2.5.11 GLASS SAND:

Surendranagar: Major glass sand deposits of the state are in this district. The sand is white, friable and present in the Dhrangadhra Sandstone which occasionally contains specks of kaolinised feldspar. Important deposits occur near Dhrangadhra, Godavati, Gugaliana, Ramparda, Surajdeval and Vavdi.

2.5.12 GOLD:

Jamnagar: Adye (1914) reported gold-bearing quartz veins from the Alech Hills. To exploit this gold occurrence, Alech Gold Syndicate was formed in 1950 and the efforts, after establishing the strike length of 200 feet (60.96 m) with an average of 10dwts/ton, were

abandoned. Alech Hill is occupied by basaltic differentiates such as gabbro, granophyre, rhyolite and trachyte. These are intruded by basic and acid dykes. Miliolite limestone forms the cover of all these formations. Investigation for gold by GSI (1992-93) in the area indicated gold up to 0.1 ppm in bedrock samples and 10-50 ppb in stream sediments.

2.5.13 GYPSUM:

Bhavnagar: Gypsum occurrences are reported from several localities within a radius of 16 km around Bhavnagar city. Gypsum occurs under a thin soil cover as platy crystals embedded sporadically in Gaj clays, seldom exceeding 2-3% of the entire bulk of clays. Gypseous clays are also reported from Chitra. There are two deposits, viz. Balanivav and Lunsapur in the district. Both are in free hold areas. In the Maheswari River section, gypsum occur under three to six meters thick overburden, are reported from Adhewada, Akwada, Budhel and Bhuteshwar villages.

Jamnagar: Four deposits are in this district. Bhatia, Bhopalka and Satapur deposits occur in leasehold areas and the quality of gypsum found here is of mixed type. The Virpur deposit is of soil reclamation grade whereas Rann deposit contains gypsum of various grades, viz. fertilizer/pottery, cement/paint/soil reclamation and unclassified type. The most important gypsum deposit is located at Rann where selenite occurs as streaks and veins in bluish clay, at the contact of Gaj Formation and laterite. At Virpur, selenite veins are found associated with a three meters thick marl bed, covering an area of four-square kilometers, below 1.2 m thick soil cover. The veins, up to 7.5 cm in thickness also contain fibrous or platy gypsum. Near Bhatia, 3.5 m thick selenite-bearing clay beds cover three kilometers long and 200 - 1,500 m wide area lying under a 3.5 - 90 cm thick soil cover. The many clay bands occur in the neighbourhood of Gaj Formation and laterite. Reserves of 0.175 Mt of gypsum have been estimated from this deposit. Occurrences of selenite in clay beds of the Gaj Formation have also been reported from Mota Asota and Nandana. Reserves of 0.654 Mt have been estimated for these deposits.

Junagadh: Deposits of selenite have been reported from Meda Creek northeast of Bharwada. Gypsum occurs as sporadic plates and needles in yellowish calcareous clay underlain by 0.75-1.0 m thick soil. A 0.45 m thick bed of gypseous clay is reported to occur along a 1.2 km long and 15 m wide area near Pachala. Small, but workable, occurrences of gypsum have also been reported at Balanivav, Kadiali and Lussapur. The deposits found in the district are in freehold areas.

2.5.14 LIGNITE:

Lignite is predominantly associated with grey to greenish-grey carbonaceous clay (Eocene) overlying the Deccan Traps, at Khadsalia.

2.5.15 LIMESTONE:

Amreli: Pale yellow to deep ocherous coloured marly limestone (Gaj Formation) occurs at several places (Balanivav) in stream sections. It contains abundant foraminifers, besides some corals and molluscs. The thickness of the Gaj Formation ranges from 10-150 m near the coast. Limestone of the Miliolite Formation (Pleistocene) is exposed, north of Una, in the Machhundri River and in some well sections. It contains alternate bands of micrite and calc-arenite. The thickness of limestone in the area is less than eight meter and unconfomably overlying the Neogene-Quaternary sediments is distributed over a large area. Important areas having sizeable deposits are around Chanch bet, Dantardi, Jafrabad, Kodinar, Mitiala, Vandha and Vavarup.

Bhavnagar: Limestone deposits occur around Gopnath, Mahuva, Methala, and Talaja in Miliolite Formation (Pleistocene).

Jamnagar: Highly arenaceous limestone containing abundant shell fragments belonging to the Dwarka Formation (Pliocene) occurs at Okhamandal area. Notable limestone occurrences are reported from Mithapur, Ranpur, Sikka, Dhrasanvel, Kalyanpur, Lalpur and Kuranga. Gaj Limestone is also found to occur around Gorinja, Bhimpura, Meripur and Ashapura Mata temple. Besides miliolite, it also occurs along the main coast and in the Okha-Rann.