Chapter II

GEOLOGICAL SET-UP

2.0 INTRODUCTION

The study area forms an integral part of the three major tectonic elements bordering the western margin of India such as the Cambay, Narmada and Tapi, comprising variety of geological formations, ranging in age from Proterozoic to Recent. Although majority of the geological formations are reported in the subsurface data, however the exposed outcrops belong to Deccan Traps, overlain by Tertiary and Quaternary deposits.

The geological aspects of the lower Tapi river basin have received less attention from the earlier workers. Blanford (1867) gave the earliest account on the geological attributes in his memoir on the "Geology of the Taptee and lower Nerbudda valleys and some adjoining districts", followed by Foote (1898), who had described the vast alluvial stretch between Kim and Tapi rivers. Various other contributions related to the geological aspects, directly or indirectly pertaining to the LTRB, have been provided by several workers associated with institutes such as, Geological Survey of India, Directorate of Geology and Mining, Government of Gujarat, Oil and Natural Gas Corporation Ltd., National Geophysical Research Institute, Hyderabad and the M. S. University of Baroda.

2.1 REGIONAL TECTONIC FRAMEWORK

The structural setup of the western margin of the Indian sub-continent (Atlantic-type passive continental margin, Biswas, 1982) is thought to have developed gradually on account of the breakup of the eastern Gondwanaland. This was followed by rifting of western continental margin and subsequent north-easterly drift supplemented with the anti-clockwise rotation of the Indian landmass and flood basalt volcanism, finally colliding with the Asian Plate (Mackenzie and Sclater, 1971; Bose, 1972, 1980; Powell, 1979, Klootwijk, 1979; Norton and Sclater, 1979, Veevers et al., 1980; Murthy, 1987; Biswas, 1982, 1987; Beane et al., 1986; Powar, 1987). During the earlier stage of rifting, tensional fractures were generated which were subjected to compressional stresses during the later stages of the drift, and have subsequently caused the opening of two pre-existing major fractures which resulted in the development of complex graben systems (Sykes, 1978), viz. Cambay and Narmada – Tapi graben system during early Cretaceous times (Biswas, 1987). Further, Biswas (1987) opined that these rifts, upon crustal separation became tectonically inactive, however according to Ziegler et al., (1995, 1998, 2001), it is evident that during subsequent tectonic cycles, such aborted rifts could be tensionally as well as compressionally reactivated. According to Biswas (1987), by the end of the

Cretaceous. the western continental margin of India had constituted its basic tectonic framework.

The tectonic configuration of south Gujarat (Fig. 2.1) is manifested by the two (Narmada and Cambay) major peri-continental rift basins (Kaila et al. 1981; Biswas, 1982, 1987; Kaila and Krishna, 1992), along with the West Coast Fault, which marks a major fracture zone related to the breaking away of the Indian plate from the Seychelles (Crawford, 1971; Mahoney, 1988).

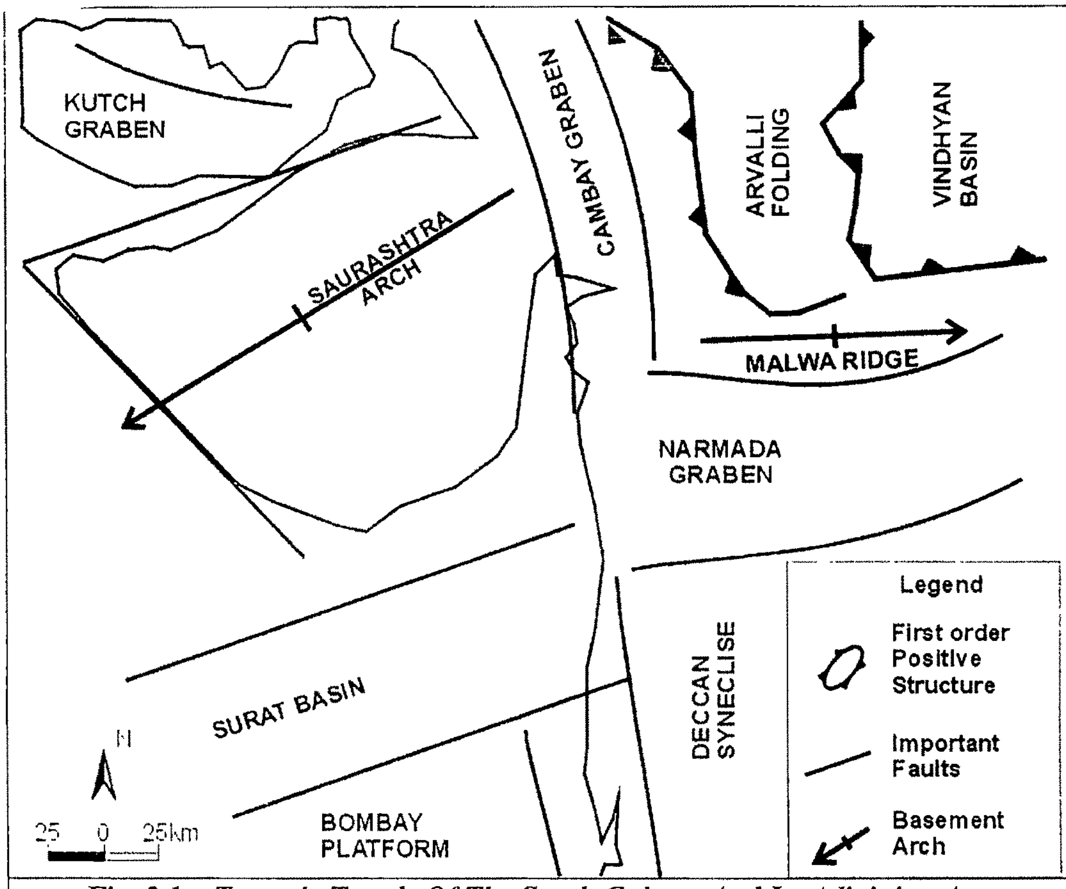

Fig. 2.1 – Tectonic Trends Of The South Gujarat And Its Adjoining Area (After Biswas, 1987)

These two major conjugate rift systems cross each other south of Saurashtra peninsula in Surat offshore region forming a deep (Surat) depression (Biswas, 1982) and together with the West Coast Fault, constitutes triple junction (Burke and Dewey, 1973; Thompson, 1976; Bose, 1980, Powar, 1987), characterized by a radial drainage pattern along with a rifted crest (Cox, 1989). These rift basins are controlled by three major tectonic trends of Pre-Cambrian Era viz. Aravalli (NE – SW), Satpura (ENE – WSW) and Dharwar (NNW – SSE).

Many earlier workers have deliberated on the basement controlled tectonics (Beloussov, 1962; Prucha et al. 1965; Eremenko, 1968; Milanovsky, 1972; Katz, 1978, Biswas, 1980, 1982) and the studies carried out by Naini and Kolla (1982) indicated that reactivation of Pre-Cambrian basement trends (NNW – SSE and ENE – WSW) has resulted in the formation of horsts and grabens in the western continental margin of India. Reactivation and subsequent block faulting along these major basement faults resulted into intra-cratonic and marginal basins, the evolution of which have been controlled and governed by repeated movement along the basement faults from time to time (Sychanthavong, 1984, Biswas, 1987). In the case of south Gujarat tectonics also, the structural style of the sedimentary basins have been controlled by the primordial fault patterns and basement grains.

The Aravalli trend is characterized by NE – SW trends which splay into three components at its southwest extremity. The main NE – SW trend continues across the Cambay graben into Saurashtra as a southwesterly plunging arch (Biswas, 1987) and probably into the Laccadives and the Maldives (Krishnan, 1960). The other two components veer clockwise and anticlockwise and coalesce into the Satpura trend in Kutch and Narmada basin regions respectively. The numerous transverse and oblique faults, uplifts and geomorphic lineaments, within the Cambay graben are manifested by the Delhi – Aravalli trends (Biswas, 1987).

The Dharwar trend (NNW – SSE), which is a dominant strike in southwestern India (Krishnan, 1960), is parallel to the faulted west coast of India. This trend comprises of a series of extension faults which are responsible for widening the western continental shelf (Mitra et al. 1983) and its northward extension across the Narmada rift resulted into Cambay graben.

The Narmada – Son lineament is a tectonic line of Pre-Cambrian origin (Auden, 1949; West, 1962), in concordance with Satpura trend (ENE – WSW). It is a major tectonic boundary (West, 1962; Chaube, 1971), featuring a mid-continental rift system (Ravishankar, 1991), which governs the structural fabric of the western India and divides the Indian shield into a southern peninsular block and a northern foreland block (Radhakrishna and Naqvi, 1986, Biswas, 1987; Powar, 1993). The Satpura trend runs between the Gulf of Cambay in the west and the Assam wedge in the east, cutting across the entire width of the Indian peninsula (Krishnan, 1960).

2.1.1 Cambay Basin

The Cambay basin is considered by the earlier workers to be a narrow linear intra-cratonic basin, located between the Saurashtra uplift and the Aravalli ranges in the west-northwest margin of the Indian shield. This basin is flanked by Aravalli ranges in the northeast, the Deccan lava flows in the east as well as west. It is oriented in a roughly NNW – SSE direction parallel to the Dharwar trend, extending along the west coast through Gulf of Cambay, as far as Ratnagiri offshore in south (Raju and Srinivasan, 1983).

This basin is bounded by discontinuous step faults on its eastern and western margins, the former being more severely faulted than the latter (Kaila et al. 1981), which are expected to continue further south in to the Gulf of Cambay as en echelon step faults (Raju and Srinivasan, 1983). The regional framework of the Cambay basin is described as "Avlokgens" of Russian geologists, which features platform structures (basins), characterized by pronounced subsidence in the earlier stages of their development, sometimes even accompanied by volcanism (Rao, 1987).

The Cambay basin, which is tectonically recognized as a half graben (Babu, 1977), was a part of the developing western Indian shelf during early Cretaceous time (Biswas, 1987). It constitutes an extensive west-sloping platform with a hinge along the eastern Cambay graben fault. The reactivation of this fault across the Aravalli range was responsible in the rifting of Saurashtra block and its subsequent uplift during the late Cretaceous, accounted for the formation of the Cambay graben, the subsidence of which started during the early Tertiary times (Biswas, 1987).

The basement faults, cutting across the Deccan Traps and continuing into the Tertiary sediments, have controlled the block structure of this basin (Mathur and Kohli, 1963; Mathur and Evans, 1964; Mathur et al. 1966; Raju, 1968, 1979; Chandra and Chaudhary, 1969; Rao, 1969; Markevich, 1976; Chaube, 1980; Kaila et al. 1981; Biswas 1982, 1987; Kaila and Krishna, 1992). The intra-basinal differential block movements along the basement fault trends have resulted in the formation of four discrete segments (Sastry et al. 1964; Mathur et al. 1966, 1968, Raju, 1968). Kaila et al. (1981), based on the DSS profiles have envisaged seven blocks bounded by deep seated faults in the southern part of the Cambay graben. Biswas (1987), has opined that the palaeo-highs formed by the subsiding blocks and volcanic centers have controlled the later sedimentation pattern of the Tertiary and Quaternary sediments in the Cambay basin.

2.1.2 Narmada – Tapi basin

The Narmada – Tapi basin constitutes the western part of Narmada – Son lineament (West, 1962; Chaube, 1971; Crawford, 1978) and is characterized by several hidden tectonic structures. magmatic crustal accretion and complex geophysical signatures (Singh and Meissner, 1995; Singh, 1998).

This basin is embayed into a narrow ENE – WSW trending graben bounded by a system of sub-parallel, dextral wrench faults (Das and Patel, 1984), slightly diverging towards the west. The DSS profile studies (Fig. 2.2) carried out by Kaila et al., (1981) between Narmada and Tapi rivers clearly indicates block faulting along a set of deep trough faults, which extends into the Moho at a depth of 35 – 40km. The subsequent reactivation along these deep-seated faults has resulted in an alternating horst and graben configuration. Mukherjee (1980) has opined that the activation along the Narmada fault was initiated during middle Eocene time, which became prominent in post Oligocene with definite indications of a fault zone in Miocene and this zone continued to the present surface. The later periodic reactivation of Narmada fault from time to time (Crawford, 1978; Ravishankar, 1987, 1991; Verma and Banerjee, 1992) has resulted in the existing structural configuration of the northern and southern area of the Narmada river (Sastry et al. 1964).

2.2 TECTONIC SETUP OF THE STUDY AREA

The study area is bounded by important tectonic elements which include the Narmada – Son lineament in the north, West Coast Fault, Eastern Cambay Basin Marginal Fault and Purna Fault in the south.

The tectonic setup of the study area is intimately related to the tectonics of Cambay and Narmada – Tapi basins thereby indicating a strong control of basement tectonic lineaments extending along ENE – WSW (Satpura trend), N – S (Cambay trend) and NNE – SSW (Aravalli trend) directions.

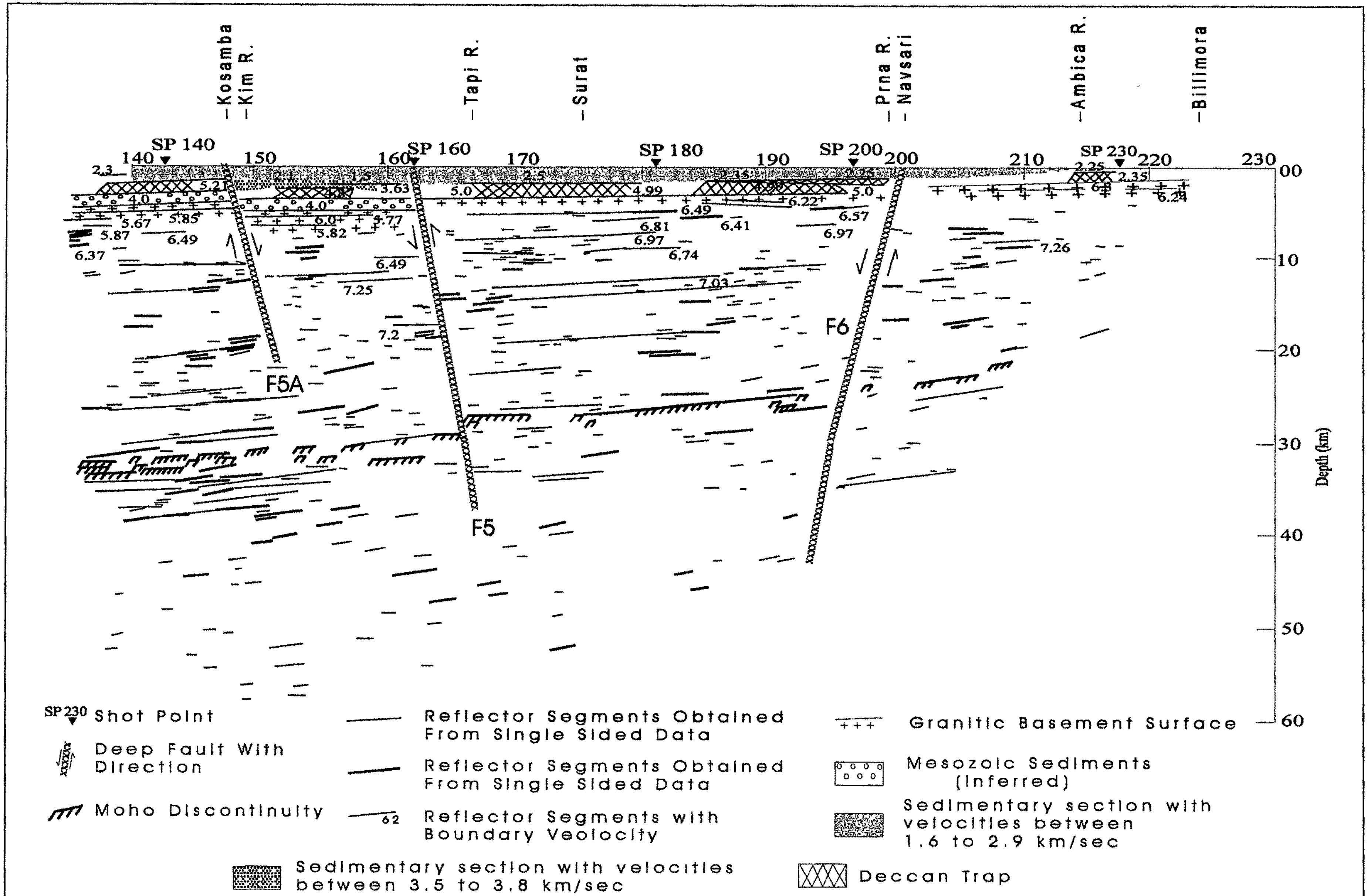

Fig. 2.2 DSS Profile Of The Study Area (Modified After Kaila et al., 1981)

The presence of dyke swarms in the Deccan Traps province (Auden, 1949, Krishnamacharlu, 1972; Karanth and Sant, 1995), the West Coast Fault (Krishnan, 1953; Crawford, 1971; Mahoney, 1988), the Tapi and associated lineaments (Blanford, 1867; Powar, 1981), fractured controlled drainage system (Alavi, 1990) and the presence of inferred "Triple Junction" (Burke and Dewey, 1973; Thompson, 1976; Bose, 1980, Powar, 1987) in the Gulf of Cambay, aptly corroborates the control of tectonism in the overall evolution of LTRB.

Earlier studies carried out on the tectonism in and around the study area provide interesting information. Kaila et al. (1981), based on the DSS profiles have divulged a steep rise of MOHO from 34km in the area south of Ankleshwar to 29km in the Tapi region and further rising up to a depth of 25km in the area north of Navsari. However, Singh (1998) has favored normal MOHO at a depth of 38km in the Navsari region and the one identified in the DSS profile (Kaila et al., 1981), probably represents the high density discontinuity where the crust has transformed into a transitional zone. Singh and Meissner (1995) have carried out the gravity studies to understand the crustal configuration of Narmada – Tapi region. According to them, the Bouger anomaly values, in this region represent a relatively broad gravity high aligned in the E – W direction and sharply fall in the area south of Tapi river, which is probably considered to be associated with Tapi graben (Nayak et al., 1986). Qureshy (1964) has considered this relatively broad gravity high to be an anomalous feature representing a horst type structure. Later Verma and Banerjee (1992) have suggested that the horst type configuration is the manifestation of the crustal upliftment associated with the movement on account of incorporation of high density basic intrusive material from the upper mantle into the middle crustal levels. Powar (1981), based on the study of the structural fabric of north Maharashtra and south Gujarat has postulated the presence of two prominent lineaments such as the Narmada lineament (Chaube, 1971) and the Tapti lineament, along the courses of Narmada and Tapi rivers, trending N 70°. Based on the lineament studies carried out by him along the western continental Deccan trap province, he postulated the deformational history and has invoked the phenomena of regional uplift, an outcome of N – S directed compression. According to him, the compression had given rise to the vertical movement of cymatogenic type, associated with arching. He has further opined that the presence of innumerable NE – SW and NW – SE trending conjugate sets of lineaments and their reactivation during various times, have resulted in the relative block movements giving rise to horst and graben configuration. These lineaments have been considered by him, to have developed in conjunction with the northward movement of the Indian plate and its impingement against the Eurasian plate. Nair et al. (1988) have envisaged the phenomenon of step faulting with throws of the order of 10 – 25m in Narmada and Tapi valleys and have suggested that these valleys represent the rifts, which have developed along the pre-existing structural weak zones.

The lineament studies using the satellite data (IRS 1C LISS III, 1998) have been carried out in the present work for the south Gujarat terrain in general and the study area in particular (Fig. 2.3). The rose diagram plotted on the basis of this data reflects the dominance of ENE – WSW lineament trends (60° – 80°) showing a consistent parallelism with the Narmada geo-fracture (Satpura trend). Majority of the trunk streams of the existing rivers show their orientation along this trend, possibly reflecting to their origin to the later reactivation of Narmada geo-fracture. In addition to the ENE – WSW trends, the other dominant trend shown by the lineaments is N – S (0 – 10°) indicating their parallelism with the Cambay trend.

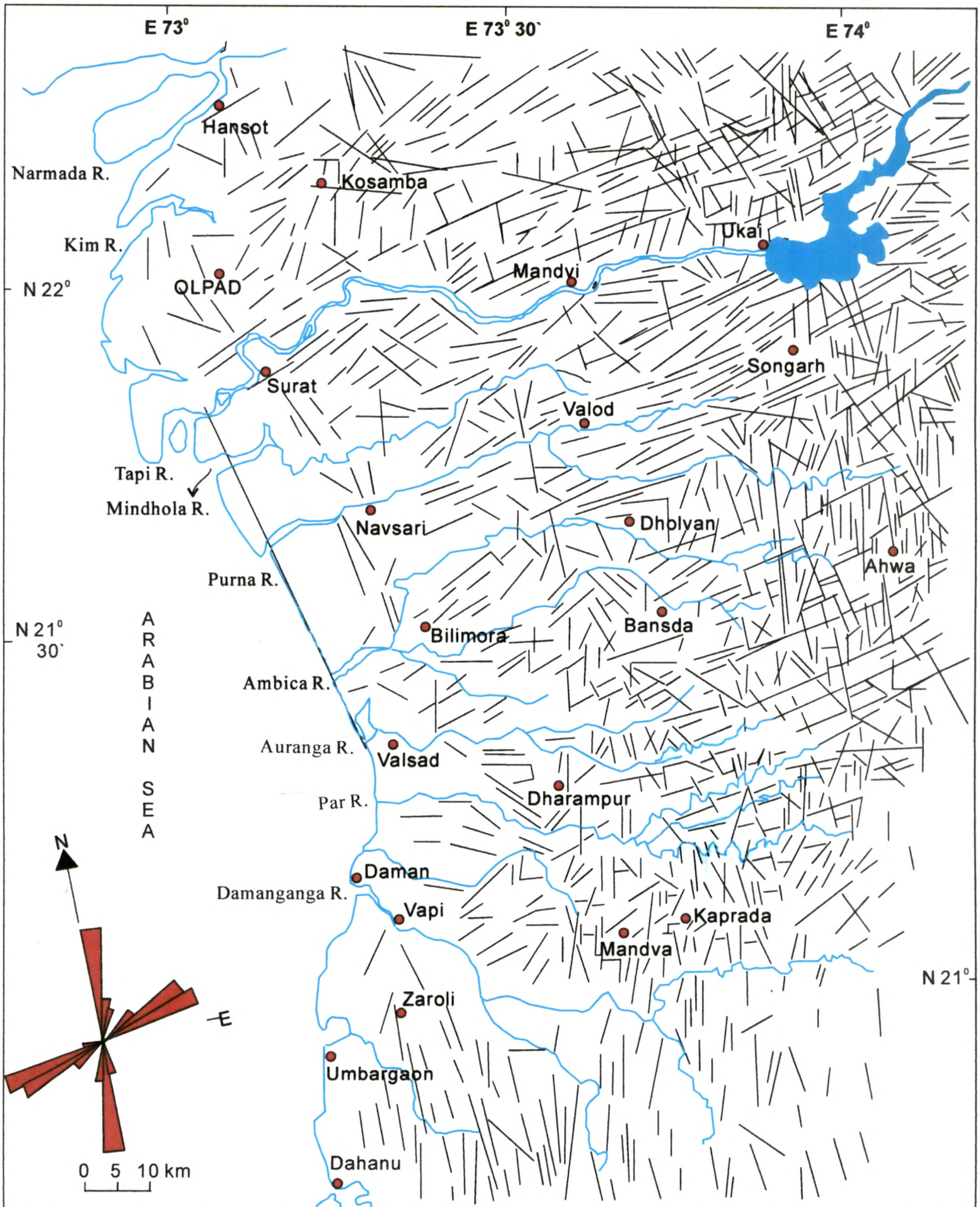

Fig. 2.3 Lineament Map Of South Gujarat, Based On Satellite Data (IRS IC LISS III, 1998)

The morphotectonic setup of south Gujarat area in general, has been prepared, based on the earlier works and the author's own observations. The schematic diagram (Fig. 2.4), clearly points to the existence of horst and graben configuration developed probably on account of the reactivation of the pre-existing basement trends and associated fracture systems.

2.3 LITHO-STRATIGRAPHIC SET-UP OF THE STUDY AREA

The study area in particular and south Gujarat in general, represents the southern extension of Cambay basin. Various workers (Rao, 1969; Chandra and Chaudhary, 1969; Gadekar, 1977; Kaila et al. 1981; Agrawal, 1984) have provided the litho-stratigraphic setup of Cambay basin. In the present study, the litho-stratigraphic succession of the study area is prepared based on the earlier works and author's field observations.

Table 2.1 provides the litho-stratigraphy of Cambay basin, whereas Table 2.2 provides the litho-stratigraphy of the study area.

Age	***Formation***	***Lithology***
Holocene (Sub-recent to Recent)	-	Soil, Clays, Silts, Sands, Gravelly sands, Gravels (Newer Alluvium).
Middle to Late Pleistocene	-	Clays, Silts, Sands, Gravelly sands, Gravels, Siltstone, Conglomerate (Older alluvium).
————	Unconformity	————
Upper to Middle Miocene	Kand	Calcareous sandstones, Shales, Marls and Limestones.
————	Unconformity	————
Upper Cretaceous to Eocene	Deccan Traps	Basaltic rocks and its varieties.

Table 2.2 – Litho – Stratigraphic Succession Of The Study Area.

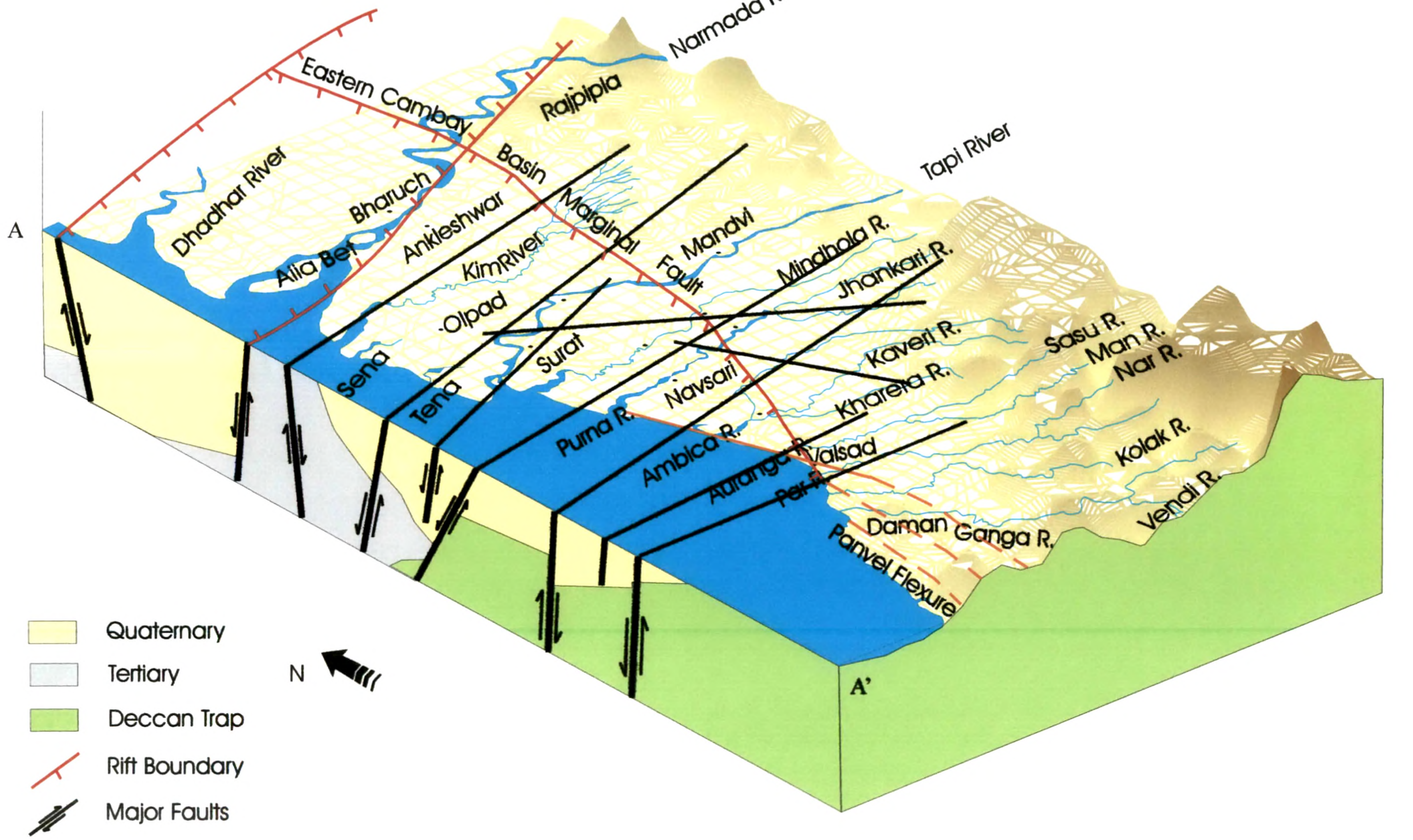

Fig. 2.4 - Block Diagram Depicting Morphotectonic Set-Up Of The South Gujarat Terrain (The Transverse Profile A - A' And The Position Of Faults Is Based On The Works After Kaila et al. 1981 And Biswas 1982, 1987).

Group	Formation	Thickness in m	Lithological Description	Age
	Gujarat Alluvium	50-100	Yellow & grey sandy clays	Recent
	Jambusar	300	Yellow & grey clays coarse sands gravel & kankar	Pleistocene
	Broach	300	Chocolate brown & red brown claystone, sandy claystone & sandstone	Pliocene
	Jhagadia	200	White & grey calcareous and micaceous sandstone, grey shale sandstone and shale	Upper / Middle Miocene
	Kand	200	Grey clay and claystone with occasional sandstone and conglomerate	Middle / Lower Miocene
	Babaguru	200	Ferruginous sandstone, conglomerates and grey clays	Lower Miocene
	Kathana	250	Variegated and mottled claystone and sandstone, carbonaceous sideritic shales and sandstones	Lower Miocene
	Tarapur / Ankleshwar	200-300	Green grey and dark grey shales, sandy shales and argillaceous sandstone South of Mahisagar river, sandstone, dark grey to green grey shales and bio-clastic limestone	Oligocene / Upper Eocene / Middle Eocene
	Kalol	200-300	Sandstones calcareous, silty shales and siltstone sideritic claystone, dark grey shales, coaly shales and coals	Middle Eocene
	Kadi Cambay Black Shale	500-1500+	Dark grey to black shale Sands, sandstones, carbonaceous shales, dark grey shales and coals Dark grey to black fissile shales, pyretic and rich in combined organic matter	Lower Eocene / Paleocene
	Olpad	20-1000+	Volcanic conglomerates, sandstones, silt, ashy claystones and clays of light grey to reddish brown and flaming red color. The matrix is clayey and chloritic. Locally carbonate enriched zones are present	Paleocene
Deccan Trap		300-1000+	Basalt-andesite, trachyte, picrite, syenite etc.	Late Cretaceous

Table2.1 – Litho- Stratigraphic Succession Of Cambay Basin (After Chandra and Chaudhary, 1969).

Figure 2.5 shows the fence diagram of the complete south Gujarat alluvial plains along with the position of Eastern Cambay Basin Marginal Fault, prepared on the basis of the available bore-hole records obtained from various state government organizations, whereas figure 2.6 depicts the surficial geology of the study area.

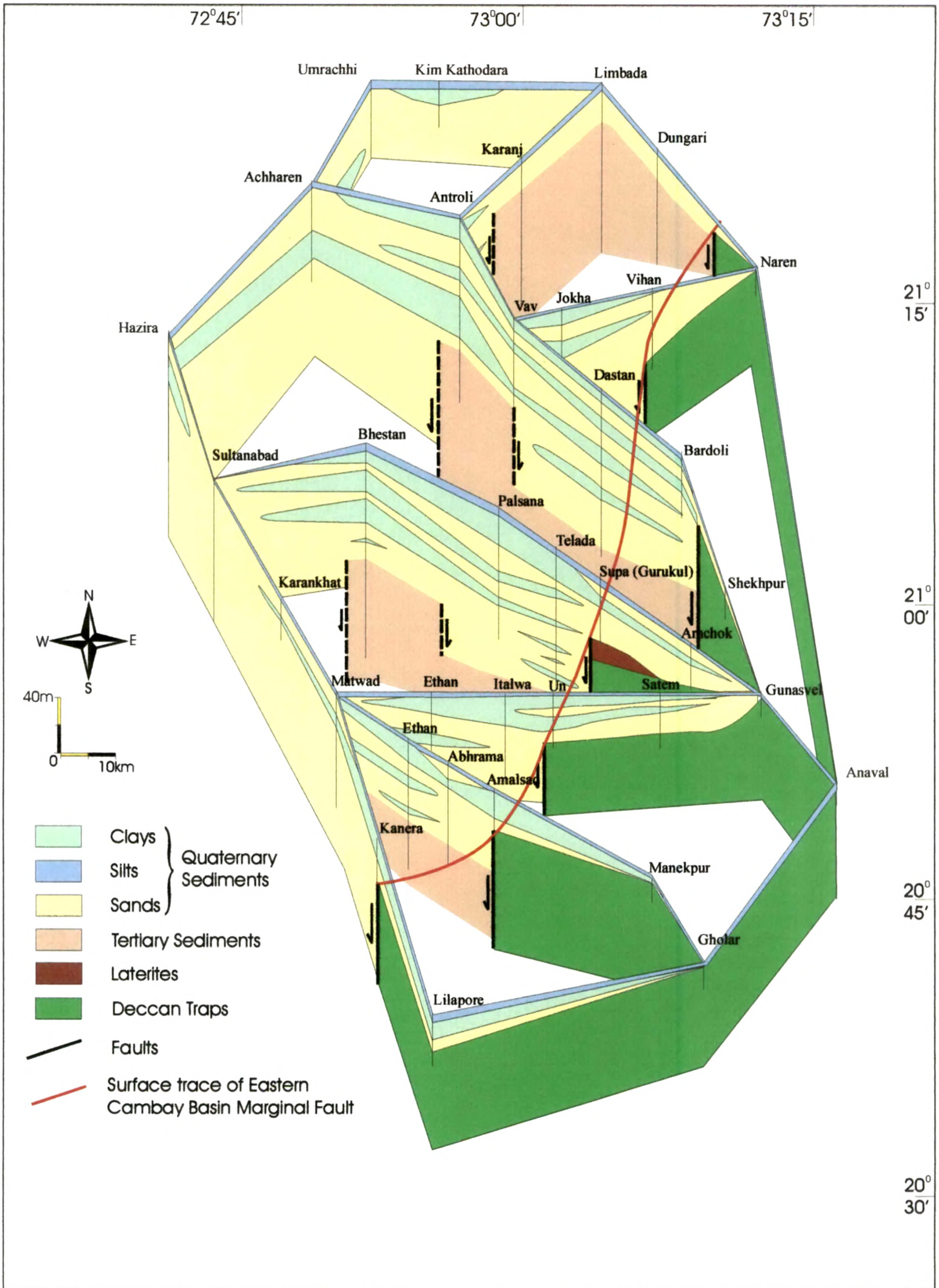

Fig. 2.5 Fence Diagram Showing Sub-Surface Distribution Of Various Litho-Stratigraphic Units In South Gujarat Alluvial Plains.

2.3.1 Description of the Stratigraphic Units

2.3.1.1 Pre-Cambrian Granites – The granitic rocks have been encountered in the sub-surface data and forms the basement for the overlying younger rocks in the study area. The DSS studies carried out by Kaila et al. (1981) points to the existence of these magmatic bodies at various depths, in south Gujarat.

In the Mehmadabad – Billimora DSS profile of Kaila et al. (1981), they have been encountered at a depth of 4.0km in Kosamba block, gradually rising to 3.5km near the present-day Tapi river channel, 2.6km near the present-day Purna river channel, in the Surat block; 2.0km in the region slightly south of Navsari and ultimately at 1.2km near Billimora.

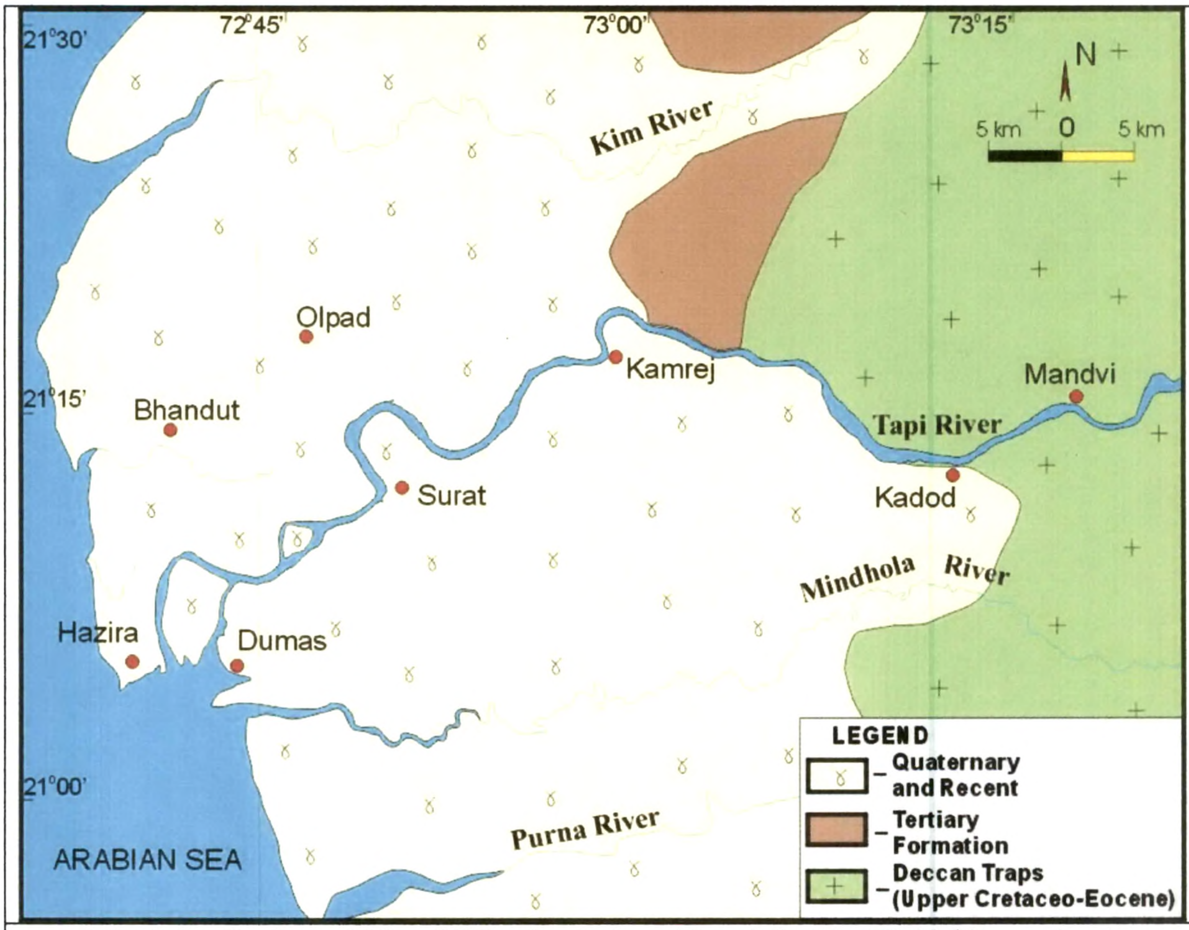

Fig. 2.6 – Geological Map Of The Study Area (Based On The Field Observations)

2.3.1.2 Mesozoic Sequences – The Mesozoic sequences are found resting unconformably over the Pre-Cambrian meta-sediments and granites. The surface outcrops of these rocks are encountered in the northern part of the lower Narmada basin, mainly represented by younger Cretaceous sediments. The outcrops of these sedimentaries include the Himmatnagar Sandstone Formation, Dhrangadhra Formation, Wadhawan Formation, Bagh Formation and Lameta Formation. Majority of the outcrops of these Mesozoic sediments are concentrated in the Cambay and the Narmada basins, however, patchy outcrops of Bagh Formation, which typically occur as inliers and outliers, are exposed in the area, south of Narmada river (around Rajpipla, Surpan etc.) also.

Within the limits of the study area, the surface outcrops of these Mesozoic sequences show marked absence, however the subsurface geophysical data has inferred their existence below the Deccan Traps (Kaila, 1988; Kaila et al., 1981; Dhar and Singh, 1990).

Kaila (1988) has inferred a hidden Mesozoic basin below the Deccan trap in the Narmada – Tapi region, which consists of two grabens, namely Narmada graben and the Tapti graben, separated by a smaller horst. The Tapti graben represents the southern extension of the Mesozoic basin and is bounded in the north by an east-west fault. In this graben, the Mesozoic sediments show a maximum thickness of around 1800m. He has further opined that the Mesozoic basin must have formed a part of a larger Mesozoic sea that extended in the shape of an arc from Sanawad – Mahan through Barwani – Sindad, Ankleshwar – Surat, Navibandar – Amreli, Kutch, Rajasthan, Sind and up to Salt Range.

2.3.1.3 Deccan Traps – The Deccan Traps form one of the world's largest flood basalt eruptions, with an outburst of enormous continental flood basalt activity, covering approximately an area of 0.8 million km^2 (Watts and Cox, 1989), with thickness varying from 1.5 to 2 km (Holmes, 1965; Kaila et al., 1981; Mahoney, 1984). These basaltic activities seem to have erupted through lava conduits, which being either shield volcanoes (Biswas and Deshpande, 1973) or a central edifice over a mantle plume or hotspot (Beane et al. 1986); filling up the irregularities of the pre-existing topography (Krishnan, 1960) of the entire western Indian subcontinent. This volcanism is believed to have occurred episodically during the northward drifting of Indian plate over the Reunion hotspot, during the late Cretaceous diastrophic episode, marking the Cretaceous – Tertiary transition (Morgan, 1981; Cox, 1983; Biswas and Deshpande, 1983). The drifting mechanism is attributed to the fragmentation of Gondwanaland during Late Cretaceous (Le Pichon and Heirtzler, 1969; Dietz and Holden, 1970; Wensink, 1973; Verma and Mittal, 1974) and rifting of the western Indian platform.

The Deccan volcanism is thought to have initiated during middle to late Cretaceous times (Wensink and Klootwijk, 1971; Sclater and Fisher, 1974) when India together with Seychelles and the Mascarene plateaus (Greater India) separated from Madagascar about 80 million years ago, however, the major outburst of this volcanic activity occurred with the separation of the India from Seychelles and Mascarene ridge, about 65 million ago (Norton and Sclater, 1979) and its movement over Reunion hotspot. Alexander (1979), on the basis of K – Ar dating of basaltic samples from different locations of the Deccan provinces, showed that the earliest Deccan activity commenced around 101±3 Ma, subsequently followed by two major episodes of extrusions viz. 65-60 Ma and 50-42 Ma respectively. Chandrasekharam (1985) has identified two major magmatic events, experienced by western continental margin, one at 93 Ma ago, characterized by acid volcanism and the other at 65 Ma ago, represented by Deccan volcanism. Recent radiometric dates show that the Deccan volcanism has occurred within a very short and restricted time span of about 3-5 Ma between 65-69 Ma (Courtillot et al. 1988; Duncan and Pyle, 1988) however, based on palaeontological data (Jagger et al., 1989), a still shorter time span (<1Ma) has been suggested.

The Deccan basalts have spread over vast areas of western, central and southern India and extending far ahead of the west coast of India up to Bombay High and even beyond (Bose et al. 1982). The Deccan Traps, with its maximum exposed vertical thickness of about 1700m near Igatpuri (Mahoney, 1984), gradually thins out in the east, whereas the DSS studies carried out by (Kaila et al., 1981), indicate that sub-surface thickness tend to decrease from 1.8km in north (recorded in Tapi river region) to 1.4km in south, near Navsari. They have further opined that trappean rocks show a noticeable rise in their subsurface elevation in the Surat block, from 1.7km in north to 1.2km and around 0.5km in south and finally cropping out on the surface, south of Billimora.

The basaltic lava flows in south Gujarat in general and the study area in particular, forms the northern extension of the Sahyadri Range, girdles the vast alluvial plains and Tertiary rocks in the east, with its surficial continuity delimited by the Eastern Cambay Basin Marginal Fault, in the west. In the study area, they represent horizontal bedded lava flows; however at places they show gentle dip ($15^{\circ} – 20^{\circ}$) towards west to southwest. Compositionally, they comprise olivine basalts, porphyritic basalts, andesites, tuffs and feldspar porphyry. They are highly jointed (columnar), fractured and are dissected by several N – S, ENE – WSW and conjugate sets of NW – SE and

NE – SW. trending dykes. These dykes are represented by olivine basalts, dolerites and epidiorite compositions and are of different generations (Auden 1949; Nair et al. 1988).

2.3.1.4 Laterites – The lateritic rocks are the product of sub-aerial weathering of the basalts under tropical conditions, which may develop with a thickness ranging from 2m to 10m with an aerial extent of few sq. km. (Pascoe, 1964). The laterites of south Gujarat are observed as outliers capping over the Deccan Traps and are exposed around Tarkeshwar, Valia, Mandvi, Ghala and Gandevi areas, rarely exhibiting a complete profile. The warm-humid climate along with the alkaline physico-chemical environment during the Neogene period is believed to be responsible for the laterisation of trappean rocks.

2.3.1.5 Tertiary Rocks – The Tertiary rocks of Cambay basin in general and south Gujarat in particular, have been studied in-depth by the earlier workers (Sudhakar and Roy, 1959; Chandra and Chaudhary, 1969; Sudhakar and Basu, 1973; Gadekar, 1977, Kaila et al. 1981; Agrawal 1984) and have been thoroughly investigated by several oil exploration companies owing to their high potential for hydrocarbons. The complete record of Tertiary sequences in the Cambay basin is comprehensively given by Chandra and Chaudhary (1969) and later modified by Pandey et al. (1993). These Tertiary sediments show sub-surface thickness of about 5000+ m (Mathur et al. 1968; Kaila et al. 1981; Biswas, 1982) and have been divided into various formations (Pandey et al. 1993).

The surface outcrops of the Tertiary sequences occur as a small stretch on the Cambay basin fringe along the Saurashtra coast in the Gogha – Bhavnagar and towards the east of the Gulf of Cambay in Jhagadia – Tarkeshwar areas. In the study area (i.e., Jhagadia – Tarkeshwar region), these outcrops are exposed between Narmada and Tapi rivers as isolated patches, dissected by the Kim river alluvium. Structurally, the exposed Tertiary rocks of the study area exhibits linear anticlinal structure trending SW to WSW, plunging SW to WSW and invariably flanked by reverse faults along southwestern limbs (Agrawal, 1984).

The Tertiary sequence in the study area commences with the Olpad formation, which unconformably overlies the Deccan Traps. The lithological assemblage comprises of volcanic conglomerates, sandstones, silts and claystones, which are indicative of shallow water environment under oxidizing conditions and rapid deposition accompanied with short transportation (Alavi, 1990)

The Nummulitic Formation (also known as Dinod Formation), overlies the Olpad Formation; best exposed around Nandev, Dungri and Dinod, and represents upper Eocene age and comprises of yellow colored fossiliferous limestones. The Nummulitic Formation is further unconformably overlained by Tarkeshwar Formation of Oligocene age, dominantly comprising of black shales. At places, the fossiliferous limestone of Nummulitic Formation are seen directly overlained by Babaguru Formation. The Babaguru Formation dominantly comprises of cherry-red ferruginous sandstones and conglomerates with clay, best exposed around Kosamba and Valia towns. The lithological characteristics indicate their formation under fluviatile conditions (Agrawal, 1984). The Kand Formation of Lower Miocene age, unconformably overlies the Babaguru Formation and is lithologically composed of calcareous sandstones, clays, marls and thin fossiliferous limestones; deposited in shallow marine environment.

The Jhagadia Formation comprises grayish-white calcareous and micaceous sandstones, conglomerates and shales of upper Miocene to lower Pliocene age and represents the youngest formation of Tertiary sequence in the south Gujarat; however, its occurrence is restricted to the area north of Tapi river.

2.3.1.6 Quaternary Deposits – The Quaternary deposits, also known as "Gujarat alluvium" (Chandra and Chaudhary, 1969), show an extensive distribution in the alluvial and coastal plains of the study area. These sediments unconformably lie over the Kand Formation; however, in the eastern fringes of the study area they extend beyond the marginal areas of Tertiary rocks and directly overlie the Deccan Traps, as evidenced by the exposed cliff-sections as well as the sub-surface data. The Quaternary deposition has concealed the subsurface geology of the Cambay basin and is controlled by neotectonism and the climate (Alavi, 1990; Merh and Chamyal, 1997). The Quaternary sediments are thickest in the central axial part of the Cambay basin (>650m recorded at Olpad, Pandey et al. 1993) and their transportation had been through the basin margin drainage system (Agrawal, 1984).

The Quaternary sediments are formed by the sub-aerial agencies, river action and marine processes and are derived from the erosion and denudation of the Deccan Traps and Tertiary rocks.

The older alluvium, probably of late Pleistocene age, represents the ancient floodplains deposits of the westerly flowing rivers of the study area. They are highly weathered and composed of calcareous crusts and silty clay, with the dominance of lime – kankar nodules in the top portion. The newer alluvium is mostly confined to the present day floodplains and lower terraces of the major rivers of the study area.

These floodplain deposits are very fertile and contain less lime and more organic matter as compared to the older alluviums (Kamath and Vashi, 1982).

The coastal plains comprises of sandy beaches, barrier ridges, coastal dunes and estuarine mudflats. The estuarine mudflats are composed of fluvio-marine deposits and occur behind the sandy barrier ridges. Further, the landward continuity of these mudflats, which are also rich in biogenic matter, has been considered to represent the Holocene strandline position (Patel, 1991). The pediment zone near the trappean highland is characterized by a thick accumulation of gravity-induced heterogeneous colluvial materials.