Chapter 1

Introduction to the Deccan Volcanic Province
and the study area
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1.1 Introduction

The ‘Deccan Traps’ of west central India- one of the greatest Cretaceous-Tertiary large-volume basaltic provinces of the world is also one of the better-studied Continental Flood Basalt (CFB) provinces. It is proposed by some (e.g. Ray and Pande, 1999) that the impact of such large-scale volcanism as the Deccan on the atmosphere and biosphere, at around the (K/T) Boundary was so profound that it was enough to wipe out the dinosaurs and many other types of organisms from the face of the Earth. Unfortunately, several Earth scientist believe that studies related to the Deccan are purely academic and of little social relevance. This may be true to the extent that the magnitude, eruption, age, duration, petrogenesis, and physical volcanology of the Deccan provide insights into the composition and dynamics of the Earth’s interior, but aspects like occurrences of groundwater, construction material, development of agriculturally rich fertile soil and important messages for the ‘future’ of the Earth and life itself belie the skeptic’s claim (Sheth, 2004).

The Deccan Volcanic Province (DVP) has an areal extent of $0.5 \times 10^5$ km$^2$ but it is speculated that it could be greater than present, some estimates being greater than $2.6 \times 10^5$ km$^2$ (Venkatesan et al., 1993). The flows belonging to the DVP cover large areas in Maharashtra, Gujarat, Madhya Pradesh, Goa, parts of northern Karnataka and Andhra Pradesh. The DVP is divided into four geographical subprovinces (Mahoney, 1988) viz. the main Deccan proper south of the Narmada River, the Malwa plateau north of the Narmada River, the Mandla lobe in the northeast and Saurashtra-Kutch plateau in the northwest (Fig. 1.1a). The province consists predominantly of tholeiite lava flows intruded by basic-, acidic-, alkaline-, carbonatite intrusions and igneous complexes. The lava pile attains a maximum thickness of over 2 km in the western part of the main Deccan subprovince (Kaila et al., 1981) and thins to 200 m in the eastern, northern and southern fringes (Lightfoot, 1985). The maximum exposed vertical thickness of approximately 1642 m amsl is seen at Kalsubai Peak near Igatpuri.
Figure 1.1(a) Map of the Deccan Volcanic Province showing the location of Kutch with respect of other sub-provinces. (b) Geological map of Kutch along with major geomorphic and tectonic features.
The lithosphere below the Deccan Traps has been measured seismically to be about 100 km thick (N.G.R.I., 1984). Deep seismic studies have shown that the Deccan Traps attains a maximum thickness of 1.5 km west of Koyna (Kaila et al., 1981). The maximum Moho depth of about 43 km is recorded in the central part coinciding with the Narmada-Tapi region (Narain et al., 1968; Kaila et al., 1981, 1985). The West Coast of India appears to be a region of Moho upwarp, producing a large, linear north-south positive Bouguer gravity anomaly (Kaila, 1989). The Moho rises to a depth of about 30 km along the West Coast (Kaila et al., 1981), and it shallows to about 13 to 14 km below the continental slope of the Arabian Sea (Babenko et al., 1981). Off Mumbai (Bombay), the crustal thickness is about 18 km (Kaila, 1989).

Large faults, flexures, dyke swarms and alkaline plugs/complexes along with high heat flow values, well-defined gravity anomalies, seismic activity and hot springs are confined to the three linear tectonic zones viz. the northwest-southeast trending West Coast belt, the east-west Narmada-Son lineament and the north-south Cambay Graben (Mahoney, 1988 and references therein). These features are related to deep-seated causes such as crustal thinning, faulting, up-warping of asthenosphere and magmatic underplating. On the basis of these features, and the geometrical arrangements of the graben structures, a triple junction has been suggested to lie in the Gulf of Cambay Basin (Burke and Dewey, 1973; Bose, 1980; Powar, 1982).

In the DVP, compound flows *sensu lato* are exposed around a triangular (Pune-Dhule-Aurangabad) region and the simple flows *sensu lato* are predominant in the peripheral regions (Deshmukh, 1988). Compound pahoehoe flows are also abundant in Saurashtra, west of the Cambay Graben (Rajarao et al., 1978) and Kutch (De, 1981). Vents in ancient CFB province are elusive (Self et al., 1997) and are virtually un-documented in the DVP. An existing hypothesis is that the flows belonging to the DVP represent fissure eruptions (West, 1959) and assumes that most feeder dykes are located along the three tectonically active zones. Hence, this model favours a polycentric eruptive history. Dessau and Viegas (1995) suggest that the east-west trending, thick dykes along the West Coast lineament could be feeder dykes to lava flows along the Western Ghats. Similarly, Bhattacharjee et al., (1996) conclude that the dykes along the Narmada-Tapti lineament served as feeders.

Physical volcanology of the flows from the DVP has recently gained considerable attention (Keszthelyi et al., 1999; Bondre et al., 2000; Duraswami, 2000; Duraswami et
al., 2001; Bondre et al., 2004 a,b; Sheth, 2006) as the study of the morphology and internal
structures of ancient flood basalt lavas can shed light on the duration and emplacement
history of these flows. Pahoehoe flows in the DVP exhibit variety of volcanic features such
as toes, lobes, tumuli (Duraiaswami et al., 2001; 2002) sheets, and tubes (Misra et al., 2001,
Duraiaswami et al., 2004). Although individual flows are often ≥ 100 m thick (Deshmukh,
1988), they are strongly compound on a local scale. Studies by Kesztethy et al. (1999),
indicate that different pahoehoe features in the DVP are very similar, both in form and in
magnitude, to their Hawaiian counterparts, leading to comparisons between the volcanic
systems in Hawaii and in the DVP (Walker 1993; Duraiaswami et al., 2001). Simple flows
(sensu Walker, 1971; Kesztethy et al., 1999, Bondre et al., 2004) in the DVP are
caracterized by near horizontal upper and lower surfaces, broad flow fronts and greater
thickness (> 15 m), when compared to pahoehoe. Internal structure of most simple flows
consists of vesicular crust with or without flow top breccia; thick, non-vesicular, dense (but
jointed) core and a sharp glassy base (Duraiaswami, 2000). Simple flows in the DVP
generally exhibit well-developed jointing patterns that are generally persistent laterally and
are referred to as colonnade and entablature (Tomkeieff, 1940). A distinct red, green or
brown horizon of soft, clayey tachylitic material commonly referred to as ‘bole’ is often
present between two simple flows. Several workers have referred to the simple flows in the
Deccan to as flows (e.g. Wilkins et al., 1994). Detailed observations of these flows however
indicate that most of them do not satisfy the sensu stricto criteria of aa (Duraiaswami et al.,
2003, Bondre et al., 2004b) and it follows that these flows could be rubbly pahoehoe flows
(Kesztethy, 2002; Bondre et al., 2004; Duraiaswami et al., In press).

Despite its large areal extent, the DVP is one of the better-studied CFB province in
the world, especially in terms of its petrogenetic history, age and recently, stratigraphy.
Detailed geochemical stratigraphy of the western part of this province (Table 1.1) divides
the ~1.5 km thick volcanic pile into twelve formations. Lithostratigraphic classification
ascribes the entire province a Supergroup status that is divisible into the Sahyadri-, Satpura-, Malwa- and Amarkantak Groups (Godbolle et al., 1996; Geological Survey of India, 1998).

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Equivalence between the established geochemical- and litho stratigraphy in the western parts of the DVP is given in Table 1. Besides the tholeiite flows in the province, minor picritic basalts (Krishnamurthy and Cox, 1977) and alkali rich flows (Krishnamurthy and Cox, 1980) are also reported. The exact stratigraphic position of the K-rich alkaline suite is however not well constrained.

Dykes along the tectonic zones are hypabyssal (Auden, 1949; Agashe and Gupte, 1972; Deshmukh and Schgal, 1988), only a few are seen to be feeder dykes actually feeding the lava flows (Crookshank, 1956; Gosh and Pal, 1984; Karmalkar et al., 1998). Bondre et al. (2006) studied the upland dyke swarms from Sangamner area and based on the geochemistry concluded that some dyke could be feeders to the flows belonging to upper formations in the Deccan. Recently, based on the discriminant-function analysis of major and trace elements of 400 dykes and 60 samples for Nd, Sr and Pb isotope ratios Vanderkluysen et al. (2006, 2007) concluded that the majority of feeder dikes were concentrated in the Nasik-Pune and coastal areas at the time of the upper formation emplacement. Intrusive acidic, alkaline and carbonatite complexes are also exposed within the tectonic zones. The Gimar complex is one such igneous complex in Saurashtra that consist of gabbro-diorite-nepheline syenite rock types (Bose, 1973; Paul et al., 1977). The Rajpipla intrusive suite of potassic alkalic basalts, mugearites and rhyolites (Krishnamurthy and Cox, 1980; Mahoney et al., 1985) and the igneous complexes (Ambadongar, Phenai Mata, Siriwasan-Nakal, Panwad-Kawant) from Chota Udaipur consisting of sodic alkalic intrusive, acidic suites and carbonatites (Sukeshwala and Avasia, 1972; Viladkar, 1981, Gwalani et al., 1995) also constitute important examples from the DVP. Alkaline intrusives in the form of nepheline syenite-ijolite plugs, alkali gabbro and lamprophyre dykes are also reported from the West Coast region of the DVP (Dessai, 1985; 1994; Dessai and Bodas, 1984, Sethna and Das, 1991).

Recent advances in precise radiometric dating, magnetostratigraphic techniques, etc., have led to the wide acceptance of the fact that the age of the Deccan tholeiite flows is 65±5 million years. However, Alexander (1981) earlier used the K-Ar dating technique and inferred that the age of lava flows ranged widely between 100-40 Ma indicating that the eruptions took place over many tens of millions of years, with the major volcanic episode during 60 and 65 Ma. Recent studies by Courtilliot et al. (1986) and Duncan and Pyle (1988) however suggests that the duration of eruption might have lasted for just a few million
years. Sheth et al. (2001a, b) dated trachyte and basalt lavas from Mumbai by the $^{40}$Ar-$^{39}$Ar technique and obtained isochron ages of 60-61 Ma. Noting that the oldest reliable ages from the Deccan are of around 68.5 Ma, they argued that the total duration of Deccan volcanism was at least 8 m.y., not 1 m.y. as often argued (Sheth, 2004). The fact that the main eruptive phase occurred during the magnetic chron 29R (e.g. Venkatesan and Pande, 1996), and lasted for around 10 million years, is gaining wide acceptance.

Eruptions of CFB’s have received considerable attention in the recent past. The DVP is no exception. The Deccan flood basalts have been linked to the Reunion plume, whose remaining tail is responsible for the present day volcanic activity on the Reunion island in the Indian Ocean (Duncan, 1981, Morgan, 1981, Cambell and Griffiths, 1990). Studies of deep-sea drilling data suggest that during most period of Deccan volcanism, the Indian plate was moving rapidly northward subsequent to the break-up of Gondwanaland (Veevers et al., 1975; Johnson et al., 1976, 1980; Powell, 1979; Powell et al., 1980; Klooitwijk, 1979; Patriat and Achache, 1984). Volcanism began in the Mid to Late Cretaceous (Wensink and Klooitwijk, 1971; Sclater and Fisher, 1974) when greater India (including the Seychelle islands and the Mascarene plateau) broke away from Madagascar (Norton and Sclater, 1979). The peak magmatism coincided with the sundering of Seychelles and the Mascarene plateau from western India at around 60-65 Ma (Norton and Sclater, 1979). Cox (1983) suggested that the northward movement of Indian plate over the Reunion plume has given rise to the observed over stepping of the stratigraphic formations. The drainage pattern is the result of uplift related to the plume activity, which is still preserved after 200 Ma. According to him the crustal thickening by magmatic underplating is the most likely cause of the presence of such uplift. His model considers an uplift of up to 2 km in the center of the dome beneath the continental areas as a result of dynamic and thermal effects of plume impact. Fracturing of dome produced many rifts and large amount of basaltic volcanism, as the anomalously hot mantle material underwent decompressive melting.

Devey and Lightfoot (1986) further modified the model of Cox (1983) with an aim of explaining the development of the N-S structure. According to them due to the impact of the plume and the subsequent underplating, the eruption of traps took place along with the separation of Seychelles from India. This was followed by the subsidence and block faulting of the crust west of Western Ghat ridge as well as the gentle tilting of the crust eastwards as the Western Ghat ridge was uplifted. This resulted into a lava pile that no more remained
flat lying, but formed a very low amplitude anticlinal fold structure caused by the deformation of Deccan Traps after their eruption.

The model by Beane et al. (1986) differs slightly from that of Devey and Lightfoot (1986). According to their model, all the observed dips of the traps are primary in origin. These workers also proposed a gentle anticlinal fold structure. They further commented that the lensoid shape of many formations and the nearly random orientation of the feeder dyke system (Hooper, 1990) indicated that the Western Ghats could be the center of the volcanic edifice formed as the Indian plate drifted northwards over a hotspot. Subsequent model proposed by Mitchell and Widdowson (1991) support the model of Devey and Lightfoot (1986) based on the mapping of high and low level laterites. In all the above models, one aspect is common i.e. the plume related uplift and magmatisim preceded rifling.

In contrast to the above models, based on the composition and orientation of the dykes on the western margin, Hooper (1990) envisaged that the main tholeiitic phase preceded significant extension and crustal thinning and the separation of Seychelles from the Indian subcontinent is therefore subsequent to the volcanism. Further, Hooper (1990) suggested that the dyke swarm trending north to north-west and parallel to the West Coast, which cut flows of the Deccan basalts, reflects a period of east-west extension that is younger than the main eruptions of flood basalt and corresponds in age to the first oceanic crust to form between the Indian- and Seychelles plates. The east-west extension eventually led to the separation of the continental plate into Indian- and Seychelles plates and to the eruption of oceanic tholeiites.

Since the recognition of the fundamental importance of flood basalts, extensive modern-type studies of the Deccan by many Indian and foreign research groups began in the early 80's or so and have continued unabated (see reviews by Chandrasekharam, 2003, Sheth, 2004). Intense studies of the lower crustal and upper mantle xenoliths are being pursued world over as these provide a clear picture of the inaccessible parts of the Earth's crust and upper mantle. Xenoliths in lavas and intrusions provide the most direct evidence of the interior of the Earth. Studies on xenoliths of both crustal and mantle origin, especially related to the DVP are few and are quite fragmentary. Examples of upper crustal fragments are known from the basaltic dyke exposed in the Narmada River at Mandaleshwar (Fig. 11a) which lies few hundred kilometers to the southeast of the Kutch region (Duraiaswami and Karmalkar, 1996, Subbarao et al., 1999). The basaltic dyke here
exposes large angular upper crustal xenoliths of granite and quartzite. These are closely similar to the Upper Proterozoic sequences of the Vindhyan exposed nearby and provide evidence that such rocks formed the basement for the Deccan volcanism. The large size of the crustal xenoliths probably is a consequence of the lower density and hence greater buoyancy of the upper crustal rock types. The geophysical studies across the Narmada River confirm the presence of thin crustal ‘granitic’ layer underlyng the thick crustal ‘basaltic’ layer. Granite and rhyolitic xenoliths are also reported from dykes from Pune-Ahmednagar region (Sharma et al., 1999). Similarly, unusually rich crustal xenoliths of great lithological variety (gneisses, quartzites, granite mylonite, felsic granulite, carbonates and tuff) representing a highly heterogeneous heteroreto unreported Precambrian basement below the Deccan Traps is reported from the Dhule region (Ray et al., In Press).

Occurrences of mantle xenoliths in volcanic rocks belonging to the DVP are apparently few but have attracted much attention. Lower crustal mafic and felsic granulites and lower mantle websterite and pyroxenite xenoliths from the lamprophyres from Murud-Janjira, West Coast dyke swarm are reported by Dessai et al. (1999) and Dessai et al./ (2003). These xenoliths have yielded a temperature range of 500-900°C and pressures of 6-11 kbar corresponding to a depth of 20-35 km. The Peninsula of Kutch is another important locality where ultramafic xenoliths are found in alkaline plugs. Krishnamurthy et al., (1989) were the first to discuss the mineral chemistry of four xenoliths from Kutch. Karmalkar et al. (1999) reported the occurrence of spinel platelets and highly birefringent rutile inclusions in the orthopyroxenes of spinel lherzolite xenoliths from Sayala Devi in Central Kutch. They interpreted the occurrence of enigmatic orthopyroxene-rutile-spinel intergrowth to be a low-pressure, low-temperature exsolution phenomenon related to the onset of mantle metasomatism. Chandrasekharam and Vinod (2000) showed the interesting petrographic features of the Kutch clinopyroxenite xenoliths and compared them to a rock from Mumbai that contains what they considered clinopyroxenite xenoliths/xenocrysts. The inferences drawn from the xenoliths from the DVP are area-specific and are entirely based on the petrological studies. The information thus available about the deep lithosphere is quite sketchy. A holistic approach involving both the xenoliths and the geophysical data perhaps would make the picture clearer. Xenolith data allow construction of geotherms and stratigraphic profiles and provide lithological constraints and physical parameters for realistic interpretation of geophysical data (Griffin and O'Reilly, 1987, O'Reilly et al., 2001). Considering that one such attempt has been made along the West Coast region
(Dessai et al., 2004), it became imperative to undertake similar studies in Kutch. This is the take-off point for the present investigation.

1.2. The study area

Kutch derives its name from the Gujarati term ‘Katchha’ which literally means a tortoise. The name has come into existence due to the peculiar shape and geomorphology of the area. The district of Kutch comprises about 24% of the total area of the state of Gujarat and shares its northwestern and northern border with Pakistan. The Arabian Sea is present to the west and southwest and the Gulf of Kutch is present to the south of the district. With a total area of 44,203 km² it is the second largest district in India, next only to Ladakh in Jammu and Kashmir. Poor rainfall, aridity, drought and salinity have left an indelible mark on the landscape of the district. Administratively, the peninsula of Kutch is divided into three sub-divisions and 11 talukas. Physiographically, Kutch can be divided into the Kutch Mainland, the Banni plains, the Island belt within the Rann (salt wastes) and the Rann.

The study area lies in the central part of Kutch Mainland and is bound by latitudes 69°10’00” and 69°55’00” and longitude 23°12’00” and 23°30’00” and covers parts of Survey of India toposheet numbers 41 E/3, 41 E/4, 41 E/7, 41 E/8, 41 E/11, 41 E/12, 41 E/15 and 41 E/16.

1.3 Climate

The semi-desert area of Kutch has a very low average rainfall and faces chronic scarcity conditions for want of adequate rains. Kutch has an average annual rainfall of approximately 395 mm. The annual rainfall varies from 420 mm at Mandvi on the southern coast to 334 mm at Lakhpat on the northwestern coast. About 95% of the annual rainfall in Kutch is received during the southwest monsoon season. July is the rainiest month of the season. On an average there are 16 rainy days (days with rainfall ≥ 2.5 mm) in a year in the district. As the Tropic of Cancer passes through the northern parts of the district, the area has an intensely hot or cold climate. The temperature ranges from 2°C in the winter to 45°C in the summer. The highest maximum temperature recorded at Bhuj was 47.8°C on May 26, 1886, while the lowest minimum was -0.2°C recorded on January 28, 1977. The humidity varies from 60% in the coastal parts to about 25% in the interior parts of Kutch. Winds blow from west or southwest during the period April to September, but during the rest of the year
winds blow from directions between southwest and northwest and occasionally from north and northeast.

1.4 Physiography

The Kutch Peninsula preserves diverse landforms and is a classic example of tectonically sculptured landscape. The physiography of Kutch is a manifestation of the alternating uplifts and depressions aligned in the east-west direction that divide the Peninsula of Kutch into four major sub-units. From south to north, these are the Coastal plains, the Hilly region, the low-lying Banni plains and the Ranns.

The coastline of Kutch extends for about 352 km and constitutes the low-lying Coastal plains. Mud flats and tidal plains constitute the ~30 km wide Coastal plain. These are prominent all along the southern coast (Gulf of Kutch), the low-lying area on the west and east of the Kutch Peninsula. There are several small and big creeks of which the Kori creek is the largest.

The hilly region of Kutch is generally divided into three distinct units viz. the Island belt, hilly Mainland and Wagad. The Island belt lies to the extreme north of the Peninsula and consists of a chain of islands of which the Pachham, Khadir, Bela and Chorar islands are prominent. Kaladongar (465 m amsl)- the highest peak in Kutch is in the Pachham island. Between the Banni plain and the Coastal plains lies the Kutch Mainland. It extends as a rugged hilly terrain running in the east-west direction. Several hill ranges, domes and isolated peaks constitute this zone. Hill ranges occur in two distinct belts in the Kutch Mainland; one to the extreme north bordering the Banni plains extending from Lakhpat in the west to Lodai in the east. This hilly tract contain the famous domes like Jhura, Jamara, Panjal, Keera, Lyari, Chari, Jhurio, Habo, etc. The other hilly tract extends from Lakhpat to Anjar and contains the Central Highlands and Katrol hill. On the Kutch Mainland there are several isolated hills like Dinodhar Dongar (388 m amsl), Waral (388 m amsl), Dhrubiyar hills (388 m amsl), but the Nanadungar (430 m amsl) is the highest peak. The Wagad is an isolated island that lies to the northeast of the Kutch Mainland. It consists of few hills and rocky outcrops of sedimentary rocks. The Banni plains extend from the boundary of the northern hilly Kutch Mainland up to the Island belt and Wagad. They constitute large tracts of raised fluvio-marine sediments that support luxuriant growth of grass.

The Rann or 'salt wastes' are singularly the most spectacular geomorphological feature of the Kutch Peninsula. The Rann rises for about 2-3 m amsl and is dry for most of
the year. However, in the monsoon the Rann is flooded and is converted into an extension of the Arabian Sea. There are two distinct geomorphic expression of the Rann. The larger Rann extend from north of the Banni plains bordering the Kutch Mainland and extend beyond the Island belt up to the Nagar Parkar ridge in Pakistan. This is called the Great Rann. The Great Rann is open to the Arabian Sea through the Kori creek. Towards the east and southeast of the Kutch Mainland lies the Little Rann. The Little Rann is open to the tidal influence of the Arabian Sea through the Gulf of Kutch. Large tracts of the Rann are converted into salt pans. Almost 24% of salt in India comes from the Little Rann of Kutch.

Excepting the Coastal plains, all the other major physiographic divisions are present in the study area. The various landforms and drainage characteristics are described in detail in the subsequent paragraphs so as to acquaint the reader with the general features of the terrain – some of which have developed due to the tectono-magmatic evolution of the region.

1.4.1 Landforms

The landscape of Kutch is a manifestation of landforms carved primarily by tectonic forces. Within the study area several macroscopic landforms like the Katrol hill range, the Habo and Jhura domes and isolated conical hills are present. The Katrol hill is a prominent east-west feature in Central Kutch and is a major water divide for the north and south flowing rivers. In the study area, the Katrol hill extends from east of Bharasar to west of Syedpur. Several hills like the Satpura Dongar (262 m), Jogi Timba (22 m), Marutonk (263 m) and the Katrol hill (349 m) constitute the Katrol range. The northern flank of the Katrol hills shows excellent development of hogback and cuesta landforms.

The Habo hills constitute the Habo dome to the northeast of the study area. It extends between the Kasawali River in the east and the Pat River in the west. It rises to an elevation of 298 m. Several large and small streams originate in the Habo hills in a radial pattern. The streams draining the northern slope drain directly into the Banni plains while those originating on the western, southern and eastern slopes converge as larger rivers that drain into the Great Rann.

A large tract of hilly terrain occurs between Pat River in the east and Bukhi River in the west. The hilly tract is referred to as the Jhura hills, named after the Jhura village. The Jhura Dome proper lies south of village Palanpur and extends between the Kaila River in the east and the Nirona (Trambo) River in the west. The dome attains a maximum elevation
of 324 m asml. Some streams that originate and drain the northern flanks of the dome have developed rapids and falls, some as high as 10 m. Towards the north of the Jhura hills, a east-west trending, narrow hill range with steep flanks is present. The sandstone strata exposed in this hill show steep dips and joint swarms that are highly silicified. All these features probably indicate that the hill represent a deep seated fault zone.

A number of isolated conical hills are strewn all over the study area. An isolated, conical hill called the Galpadhar hill (257 m) occurs towards the extreme east of the study area, about 10 km northeast of Bhuj. In the central part of the study area, a group of four conical hills, all exposed in a northeast trending zone are exposed north of Sumrasar. The conical hill to the northeast of Sumrasar is the largest of the four and is called the Waral Dongar (344 m). Several linear ridges, representing igneous dykes occur near the Waral hill. The Central hill is called the Vican hill and rises to an elevation of about 299 m. It has steep conical flanks of sedimentary rocks, but the summit exposes an igneous plug. To the left of the Vican hill is the Vinchhio hill (355 m). To the extreme left of the Vinchhio hill is the Eklia Dongar, which rises to an elevation of about 184 m from the surrounding plains. Another isolated conical hill is also exposed south of village Payarko in Central Kutch. It is called the Karinga Dongar (278 m).

To the western part of the study area several conical hills are present. The Dinodhar Dongar is probably the largest conical hill in the study area. The hill towers to an elevation of 388 m asml and is a major landmark that dominates the picturesque northwestern landscape. Northwest of Vironi, another small conical hill—the Pakhdai Dongar (258 m) is present. The conical hill consists of steep flanks of sedimentary rocks and a summit of igneous rock. To the extreme west of the study area, another conical hill, popularly called the Manki Dongar (311 m) is present south of Wehar.

Several flat-topped conical hills are also present around Nakhatrana. The most prominent of these is the Dhodam Dongar (271 m) referred to by the locals as the ‘Dhram’. In the hilly terrain south of Nakhatrana, two prominent conical hills namely hill 334 m northeast of Masung and hill 363 m northeast of Sukhsan are noteworthy. A couple of isolated conical hills also occur in a linear belt north of Mangwana. These are hill 350 m northwest of Vijapsar and Seyala Devi (326 m) north of Mangwana. South of Mangwana three isolated hills are present. The eastern most is called the Gurukul Dongar (295 m), the central Dhruviya Dongar (348 m) and the western most the Nana hill (433 m).
Besides the isolated conical hills, several low lying, flat-topped hills are present, especially in the western part of the study area. The flat-top hills constitute plateaus and are present in two isolated regions. The first group of such flat-topped hills occurs around Roha in the southwest of the study area. The second group of flat-topped hills occurs around Kotoda in the northwest of the study area. These include the Mevo hills, Pakhdo Dongar and hills southeast of Kotoda. The elevation of the flat-topped hill varies from 160 m to 240 m. The flat-topped nature of these hills is due to the presence of lava flows on the near horizontal sedimentary rocks.

1.4.2 Drainage

The rivers from the Kutch Mainland are short and ephemeral (seasonal), and are dry for most part of the year. The Central Highlands of Kutch extending from Lakhpat to Anjar acts as the major water divide, dividing the drainage in to north flowing (into the Rann) and south flowing (into the Arabian Sea) rivers. The major north flowing rivers are Kasawali River, Pur River, Khari River, Kaila River, Trambo River, Jabri River, Bhuki River, Kadrai River and Chhari River. The main rivers that either drain directly into the Arabian Sea or through the Gulf of Kutch are Rukmawati River, Viraniwali River, Naira River, Chok River, Sai River, Vengdi River, Khurrod River, Nagavanti River, Phat River, Sakra River and Larekh Rivers. The following paragraphs describe the rivers that occur within the study area.

The Kasawali River originates south of the Habo hills, west of village Jikadi and flows in the northwest direction. Southeast of village Habo the river widens into a flat broad channel. The Kasawali River and its tributaries show rectilinear segments that are structurally controlled. West of Lodai the stream enters in to the Banni plains where it has built a large alluvial delta. Some of the channels drain in to the salt wastes (Rann) near village Umdenpar.

Several small streams originate in the high grounds constituting the Katrol hills. North of Kukma the stream join together to form the Pur River proper. The Pur River and its tributaries between Lakhond-Mota Wanara-Nagor have developed deep incision in the sedimentary rocks. The deep incision, structural control of river segments and the presence of a large plug near Galpadhar suggest that the region was probably uplifted due to the igneous intrusion. The Pat River also originates in the Katrol hills, south of Bhuj near the Satpura Dongar. The Dhurawa River also originates in the Katrol hills, near the Jogi Timba.
hill and flows northward. The Pat River joins the Pur River near the Rudra Mata reservoir northeast of Bhuj. The Ratiya River originates in the Central Highlands and flows in the north northeastern direction up to west of Bhuj. To the west of Bhuj, the Ratiya River is joined by a northwest-southeast trending stream that drains the high grounds forming the Median high in Central Kutch (Fig. 1.1b), northwest of village Ratia. After this confluence the river is called Khari River. North of the confluence, the tributaries joining the Khari River show deep incision in the sedimentary bedrock. The Khari River meanders its way in the northwest direction where it meets the Pat-Pur River near the Rudra Mata temple. After the confluence of the Pat-Khari-Pur River, the river enters the Banni plain. Strangely it changes course in the plains and flows northwestwards to build a large alluvial fan before draining into the Rann.

The Bhurud River originates in the Central Highlands of Kutch Mainland and flows in the northeast direction. Several segments of this river are structurally controlled. The course of the river is drastically changed, as it has to circum-navigate the Waral hill north of Sumrarsar. North of the Waral hill the river is called Kaila River. The Kaila River meanders its way through the Jhura hill. Southwest of Jhura village the channel width of the river broadens. It builds a fairly large alluvial fan northwest of village Jhura.

The Vendadi River originates amongst the Gursukul Dongar, Dhrubiy and Nana hill west of Deshalper and the hilly terrain west of Manjal. The Vendadi River flows in the general north direction up to Thorwada village, from where it flows in the northeast direction. The Ghandi River joins the Vendadi River, northeast of Thorwada. The Ghandi River is a small river, which originates north of Samatra. Southwest of village Nirona the Vendadi and Ghandi River meet to form the Nirona (Trambo) River. The Trambo River is dammed in to a large reservoir. A couple of waterfalls having drop of 5 to 8 m are seen in this stretch. West of Nirona village, the river width broadens in the Banni plains, before discharging in to the Great Rann. The Jabri River is a small river that drains the Rojiman and Dhar Dongar areas north of village Bibar.

The Bhuki River originates in the hills south of Nakhatrama. Like most rivers that empty in to the Great Rann, the Bhuki River also flows in the northeast direction to meet the Rann. The river flows past the eastern flank of the mighty Dinodhar Dongar near Bhimsar. In this stretch, the course of the riverbed broadens significantly and the river meanders considerably. A few structurally controlled linear segments are also present. The Gumur River- a major tributary that drains the area west of the Jabri River joins the Bhuki River.
The Kadrai River is not as long as the other rivers but is an important river in the western part of the study area. The river originates north of Nakhatrana and flows northwards towards the Great Rann. Numerous streams that drain the western flanks of the Dinodhar Dongar join the Kadrai River. The Rukmawati River and Viraniwali River originate to the south of the Nana and Dhrubia Dongar and drain southward into the Gulf of Kutch.

The drainage pattern of rivers and streams from the study area provide an interesting aspect into the lithologic and tectonic control. In general, dendritic pattern is common in homogeneous sedimentary rocks. However, several rivers and their tributaries deviate from this general drainage pattern and show effects of structural control. Segments of rivers have developed rectilinear drainage pattern. Others have developed trellis pattern. A striking feature of the drainage from Kutch is the occurrence of radial drainage patterns. Closer observations of these indicate the presence of isolated hillocks that are responsible for this peculiar pattern. Such hills are observed at Dinodhar Dongar, Nana, Dhrubia, Waral, Vichan, etc. The isolated hills are in fact igneous plugs that have intruded the Mesozoic sediments. Centripetal drainage pattern is also seen at a few places such as, northwest of village Ratia and east of Vethon. It is speculated that these occur at the margins of the Median high (Fig. 1.1b) and it is speculated that such anomalous drainage patterns may have developed due to subsurface emplacement of large plugs/plutons.

1.5 Geology

The geology of Kutch is synonymous with the extensive Mesozoic sediments and their paleontological content. The Kutch basin is considered to be a peri-continental basin in the western part of Gujarat in Peninsular India. Sedimentary rocks are exposed extensively in the Kutch Mainland, Wagad and the Island belt of Patcham, Bela, Khatir and Chorar (Fig. 1.1b). The rocks range in age from Middle Jurassic to Lower Cretaceous. Waagen (1873-75) initially studied the fossil assemblage from these rocks and divided the sedimentary sequence into Patcham, Chari, Katrol and Umia "groups". These formations range in age from Bajocian to at least Albian (Krishna et al., 1983). The Patcham formation comprises of approximately 325 m thick sequence of limestone and shales intercalated with bands of golden oolite. The Basement-Patcham unconformity is not exposed in the Kutch Mainland. The Chari formation overlies the Patcham formation and consists of about 300 m thick succession of limestone, sandstone and gypseous shales. Rocks belonging to this formation are extensively exposed in various domes (Jara, Jumara, Nara, Kera) and in the
Katrol hill area (Walakawas, Ler). As per Waagen's classification the Chari formation is unconformably overlain by Katrol formation (Krishna and Pathak, 1991).

Spath (1933) revised the work of Waagen and further subdivided the units by ammonite zones referred to as Macrophalus "Beds", Rehmani "Beds", Anceps "Beds", etc. However, precise stratigraphic terminology was lacking even despite this revision. This confusion in terminology and disregard for stratigraphic nomenclature continued unabated and terms such as "Series" and "Stages" were in vogue. Rajnath (1932, 1942) redefined the Umia Series and created an additional unit referred to as Bhuj Stage, which included non-marine beds with plant fossils of "Middle Cretaceous" age. Although the Bhuj Stage was rightly separated in stratigraphic terms by Rajnath (1942), it was established on wrong assumptions based on local observations and completely neglected the sedimentary facies concept.

In the early 1970's, Biswas disagreed with the existing stratigraphy of the Mesozoic sediments from Kutch due to lack of precise definition, proper stratigraphic terminology, regional mapability and correlatability. Subsequently, Biswas (1971, 1977) introduced formal formation names like Jhurio Formation, Junara Formation, Jhuran Formation and Bhuj Formation based on lithostratigraphy in accordance with the recommendations of the International Subcommission on the Stratigraphic Classification (Hedberg, 1972). According to such a classification, the Jhurio Formation (named after Jhura Hills) was defined as a thick sequence of limestone and shales with bands of "golden oolite" in the lower part of the Mainland stratigraphy. The Junara Formation was named after its type section in Junara hills north of Junara village and consists of a thick sequence of argillaceous rocks overlying the Jhurio Formation. Biswas (1977) considered the "Chari Series" of Junara dome equivalent to Junara Formation. According to Biswas (1977), the Jhuran Formation comprised of a thick sequence of alternating beds of sandstone and shale. The Dhosa Oolite Member below the sequence and non-marine sandstones of Bhuj Formation above defined the Jhuran Formation. The youngest formation in the Mainland was called the Bhuj Formation consisting of a thick sequence of non-marine sandstones mostly deposited in the fluvio-deltaic environment. The Bhuj Formation was divided into three informal members-Ghuneri-, Udra-, and upper-members. The Udra Member was a marine lithosome developed locally within the formation dovetailing with the portions of the Ghuneri and upper members.
Biswas (1977) interpreted the different stratigraphic units as interdigitating lithosomes of a sedimentary complex representing different depositional environmental regimes within a peri-continental embayed basin. According to Biswas (1977), Bathonian to Oxfordian (represented by Jhurio- and Jumara Formation in Mainland Kutch) was the period of marine transgression, where the environment changed from littoral to neritic. Post Oxfordian to Lower Cretaceous (represented by Jhuran- and Bhuj Formation) was the period of regression shifting the environment from neritic to fluvo-deltaic as the depocentre moved out westward. Based on the lithostratigraphy and facies concept Biswas (1977) also concluded that the sea transgressed from west to east and receded westward after attaining peak transgression in Callovian.

According to Dubey and Chatterjee (1997), the sediments belonging to the upper sequence (Katrol and Bhuj formations) have been derived from the granite-syenite rocks of the Nagar-Parker massif, whereas the sediments belonging to the lower sequence (Patcham and Chari formations) were derived from the metamorphic terrain of the Aravalli ranges. Based on the study of heavy mineral assemblage form the siliciclastic sediments (Patcham and Chari fm.) from the Jhura dome, Mishra and Tiwari (2005) concluded that these have been derived mainly from two lithologically different Precambrian terrains- one dominated by metamorphic rocks and the other igneous (acid/basic), besides a little contribution from sedimentary rocks.

1.6 Structure and tectonics

The Kutch region is situated to the northwest of the main Deccan Trap province and proximal to the Cambay Triple junction. The structural style of the basin is very distinct and different when compared to the other contemporaneous basins in India. The structure of the Kutch region received little attention initially where more emphasis was given to the paleontological aspects. Wynne (1872) was a pioneer who mentioned about three anticlinal ridges in Kutch. Hardas and Mehra (1969) described the structural features of the Katrol hill (Charwar Range). However, details of the structural framework and tectonic features of Kutch were described subsequently in the classical works of Biswas (1971, 1980). According to Biswas (1980), the Kutch basin is bound by first order structural elements like Radhanpur-Barmer Arch in the east, Tharad-Nagar Parkar Ridge in the north and Khatiawar uplift in the south. Within the framework of the first order features seven major second order uplifts and intervening lows define the main structural units. The uplifts are bound by
quasi-vertical master faults along one side and are characterized by marginal flexures that in turn are cross-folded to produce the string of domes, brachy-anticlines and doubly plunging anticlines. Basic igneous intrusions are associated with these structures. The uplifts are also dissected by small tensional faults; shear faults and dykes of different generations.

Biswas (1980) also described a first order structural feature in the form of a meridional ridge called the ‘median high’ (Fig. 1.1b). This high expresses itself as a broad ridge and extends from NNE to SSW across Pachham, Banni, Kutch Mainland and Gulf structural elements imparting a bilateral symmetry to them. The larger structures exposing the oldest sediments in the uplift areas (Jhurio and Hībo anticlines of Mainland and Kaladongar anticline of Pachham) are situated on this ridge. Most secondary faults, intrusive plugs and dykes occur along the crest of this high. The median high expresses itself as a geomorphic ridge in the Banni plains and divides the Rann into an eastern part closed basin and a western basin open to the tidal influences of the Arabian Sea. According to Biswas (1980), the median high has played a considerable role in the sedimentary tectonics of the region. Biswas (2005) attributes the median high to be the geomorphic expression of a magmatic body.

In the regional context, Kutch is considered to represent a rift basin that extends approximately 250 km in the E-W direction and approx. 150 km in the N-S direction. According to Biswas (2005), the Kutch basin is a fossil rift at the southern end of the Indus shelf that evolved within the Mid-Proterozoic-Aravalli-Delhi fold belt by reactivation of pre-existing faults along NE-SW trend of the Delhi folded belt that swings to E-W in Kutch. Biswas (2005) presented a conceptual domino-listric model of Kutch rift based on structural and detailed depthwise analysis of aftershock data. Structurally, the basin contains footwall uplifts and half-graben along intra-basinal strike faults. Powar and Patil (1980) studied the LANDSAT-1 imagerys (1:1,00,000) from the Kutch-Kathiawar region and concluded that the structural fabric of area is characterized by lineaments dominantly trending N70° and N330° with subordinate number of lineaments oriented in the N15° and N270° directions. Facture trends can reflect the nature of the tectonic forces responsible for their development (Cloos, 1955; Badgley, 1962). Powar and Patil (1980) therefore concluded that the lineaments trending N70° and N330° might represent conjugate shears developed in response to compressional stress oriented in the near north south direction. Horsting effects are indicated by the lineaments oriented N0° to N15° and perpendicular to it. Since both the
lineament trends are present in the Kutch region, it follows that the regional structural fabric is a combination of compressive forces and vertical movements. According to Biswas (1987), the structural framework of Kutch is a result of interplay between three important Precambrian tectonic trends viz. the NNE-SSW trending Delhi-Aravalli trend, the ENE-WSW Narmada-Son trend and the NNW-SSE Dharwar trend.

The tectonic evolution of the Kutch region has been attributed to the rifting process and the region accordingly marks the site of paleo-rift graben whose evolutionary history dates back to the Mesozoic times (Taiwani and Gangopadhyay, 2001; Sengor and Natal, 2001). The Kutch basin is said to have evolved in two major stages. The first one, described as rift stage where the rifting process began during the extensional phase of the break-up and separation of Indian plate in Late Triassic-Early Cretaceous time followed by syn-rift sedimentation. The second is the inversion stage in Late Cretaceous, when the rifting was aborted and the basin uplifted (Malik et al., 2000; Maurya et al., 2003). The Kutch rift basin is proposed to have evolved in three stages by Biswas (2005):

a) an extension rift phase, when Mesozoic sedimentation took place,
b) Late rift divergent wrench phase, and
c) a compressive inversion stage when the present structural style evolved.

The three phases correspond to the breakup from Gondwanaland, drifting and collision of the Indian plate with the Eurasian plate (Biswas, 2005). It is believed that the primordial faults were first reactivated as normal faults during rifting phase and later as strike-slip faults during inversion stage. Biswas (2005) believes that there is more than one episode of syn-rift igneous activity followed by another phase of hotspot related post-rift igneous activity towards the close of the rifting stage around ~65 Ma.

Although the basic concept of mantle plumes originated in 1960s and 70s (Wilson, 1963; Ernst and Buchan, 2003) their role in explaining geological processes was marginalized during the plate tectonic revolution (Morgan, 1972). The 65-66 Ma DVP of western India is referred to as one of the classical examples of the initial ‘plume-head’ stage of hotspot development (Duncan and Richards, 1991; Campbell, 1998). The post-Deccan oceanic tract (Chagos-Maldive-Laccadive Ridge, Saya de Malha and Nazareth Bank, Mauritius) leading to Piton de la Fournaise or "Peak of the Furnace", Reunion Island represents the plume tail phase (Mahoney et al., 2002). Among mantle plume models, the hypothesis of plume ‘incubation’ readily accommodates a pre-flood-basalt, near-steady-state plume ever which a continent drifts, leading to accumulation at the base of the
lithosphere of a voluminous plume top that can be tapped later, when the lithosphere rifts (Mahoney et al., 2002). As per the tectonic model of Muller et al. (1993), Greater India began moving northward before 100 Ma at a super-fast rate of 150-200 km/Myr (Patriat and Achache, 1984; Besse and Courtillot, 1988). This rapid northward migration resulted in a limited plume ‘incubation’ period during which an immense plume top accumulated gradually beneath slow moving continental lithosphere (Campbell, 1998; Kent, 1992). A proposition to this model was that there would be a gradual decrease in the age of the volcanic rocks along the plume track from north to south. Basu et al. (1993) have recorded ~ 68.5 Ma ages (40Ar-39Ar ages of biotite separates) for the rocks from Mundwara and Samru-Dandali complexes, some 3 Myr older than the oldest flows belonging to the DVP. Several authors including Yoshida et al. (1995), Gnos et al. (1998), Khan et al. (1999), Mahoney et al. (2002) and references therein, have proposed that the volcanic rocks (Bibai Volcanics) from the Quetta-Zhob area, South Tethyan Suture zone of Pakistan, which is approximately 700 km north-northwest of Samru-Dandali represents an distant remnant of the Reunion hotspot obducted on to the continental margin. All these evidences suggest that the mantle plume hypothesis could be applicable to the Deccan flood basalt volcanism.

In the regional context of the DVP, several workers have linked Kutch to Reunion hotspot. De (1979, 1981), based on petrological and geochemical considerations of the nodule bearing olivine nepheline suite, linked the volcanic rocks from Kutch region to the Reunion hotspot. Subsequently, several workers like Simonetti et al. (1998) explained the geochemical characters of the alkaline rocks from Kutch vis-a-vis the Reunion hotspot (Fisk et al., 1988). Recently, Roy (2003) described the Deccan magmatism of northwestern India and argued in favour of a mantle plume origin.

Non-Plume hypothesis by Smith, (1993), King and Anderson (1995) and Smith and Lewis (1999) considered the Deccan flood basalts to be the result of large scale melt production of a thin OIB-type mantle lying just below or within the lower continental lithosphere and above the asthenosphere that feeds oceanic spreading centers. The prevalent mantle plume model for the origin of the Deccan flood basalts also came under serious attack by Sheth (1999a,b, 2000, 2007), who opined that evidences against it were strong and evidences for it equivocal. Sheth (1999a,b) proposed that the Deccan was a result of long-term continental rifting that culminated in continental breakup. In Sheth’s interpretation, the Chagos-Laccadive Ridge, the widely hypothesized plume track, is a southward-propagating fracture. Notably, Baksi (1999) has evaluated and considered questionable most (about 30
of the previous $^{40}\text{Ar}-^{39}\text{Ar}$ ages on hotspot tracks in the World's oceans (including the Chagos-Laccadive Ridge) that are routinely used by plate motion modellers (Sheth, 2004, 2005). However, according to Mahoney et al., (2002) the presence of pre Deccan, geochemically Reunion-like volcanism on the up-drift side of the Greater India in a closing Tethyan Ocean cannot be explained without the plume model.

1.7 Geophysical studies

Seismic data over the Kutch is meager in published literature and is a major constraint in understanding the deeper structure of the region. However, Raval and Veeraswamy (1996), using constraints from seismic lines to the south and east of Kutch, indicated a crust-mantle boundary lying at 35-40 km, and reported a zone of anomalously light mantle (density 3.1 g/cc) making up a thickness of ca 10 km below the boundary. According to them, this layer in turn is underlain by material with a density of 3.2 g/cc, extending for another 8-10 km. Their model suggests a gradational increase of density with depth below the crust-mantle boundary, as is observed in many volcanic areas such as eastern Australia (O'Reilly and Griffin, 1985). Chandrashekar and Mishra (2002) report the occurrence of several gravity highs and lows of Bouguer anomaly and attributed these to the fault-controlled basement uplifts and depressions. Based on isostatic regional, the crustal thickness of Kutch varies from 35 km along the coast to 44 km under the southeastern parts of the Kutch Mainland- and Wagad uplifts. However, Chandrashekar and Mishra (2002) also indicate that the circular gravity highs observed over islands (uplifts) along the Island belt fault indicate high-density rocks in the basement and represent volcanic plugs or sub-surface mafic rocks. Anand (2004) generated the magnetic total field anomaly map for the Kutch peninsula. According to him, the observed anomaly ranges from ~850 to 1000 mT, suggesting either exposed or sub-surface highly magnetic material. Anand (2004) also prepared the analytic signal map from the total field data to get an enhanced picture of the extent and distribution of the magnetic sources. The analytic signal map showed high magnetization anomalies centered over the surface exposures of the basaltic flows belonging to the Deccan Traps. But in regions where basaltic flows are not exposed, the large aerial extent of the anomalies suggests sub-surface extension of some highly magnetic rocks.

Kennet and Widyananto (1999) studied the seismic tomography of the Indian region using P wave arrival times, and found an approximately cylindrical region of lower
seismic velocities in the upper mantle to the north of Gulf of Cambay. They have interpreted this anomaly as the initial conduit through which the plume material forced its way through the upper mantle beneath the Cambay rift. The center of the low velocity anomaly lies just below the earliest alkaline magmatism, which has been directly linked to the Deccan plume by Basu et al. (1993). Kennet and Widlyantoro (1999) admit that the observed times used in tomographic inversion may tend to underemphasize the true extent of the anomaly. Synthetic modeling however suggests that the actual anomaly may be of larger geographic extent. The main low velocity anomaly, according to Kennet and Widlyantoro (1999), remains circular to a depth of about 250 km and then appears to connect with a more intense zone of lowered velocities in the depth interval down to 500 km where it extends over a region of around 800 km. Considering its overall size, the anomaly, may represent, the remains of the initial plume head which must have moved with India over the 65 Ma, since the Deccan eruptions. The Kutch region lies very close to this anomaly and could be engulfed in the margin of the plume head.

Indian Institute of Geomagnetism Working Group, (2001) undertook the Long Period Magnetotelluric (LMT) studies in Kutch to probe the deep crustal and mantle structures following the Bhuj earthquake of January 26, 2001. The study reveals a conductive layer at 10-17 km depth and a possible lithosphere-asthenosphere boundary at 100-150 km. The study also delineated undulating basement in the region with an estimated depth of 1 km in the north that dips to nearly 5 km towards south. These studies support the fact that there is considerable variation in electrical character of the lithosphere beneath Kutch and these variations could be attributed to internal rheological heterogeneity caused due to structure, tectonics, differential thermal perturbations and magmatic underplating.

1.8 Definition of the problem

The geology of Kutch continues to draw attention of Geologist, Paleontologist, Geophysicist and Geochemist. This region has revealed many mysteries of Earth history, some unique to the region others unique to the world. Many old, time-tested and new unanswered questions, however, still remain. Although several geoscientists have worked on the magmatic and allied aspects of the alkaline rocks and the ultramafic xenoliths from Kutch, these are in isolation. In case of alkaline rocks that have been previously studied, the emphasis was necessarily on the petrographic aspects and several workers have elaborately discussed these rocks with respect to processes such as magmatic differentiation. However,
the alkaline magmatism of northwestern India (including Kutch) is still considered by many to be a separate episode unrelated to the Deccan. The alkaline rocks in the CFB's world over are considered precursor to the main tholeiitic activity and are the result of plume incubation. Kent et al. (1992) suggested that the possible problem with the incubation model for the DVP is the rapid northward migration (140-200 mm/yr) of the Indian plate. The Indian plate is believed to have interacted with mantle plumes on at least two prior occasions (~117 Ma Kerguelen plume-Rajmahal-Kerguelen Plateau Basalts and ~ 84 Ma Marion plume - Madagascar tholeiites) due to which it is speculated that western India must have had a thin mechanical boundary layer beneath it at the time of its interaction with the Reunion plume. The presence of thin mechanical boundary layer may have allowed the Reunion plume to generate melt despite a limited incubation period. Kent et al. (1992) considered the limited incubation period as strong evidence to explain the apparent absence of precursor alkaline activity in the DVP and therefore concluded that the province was anomalous. Our investigations in Kutch, however, clearly demonstrate that the DVP by no means is anomalous (Karmalkar and Durali, 2000). It is strongly believed that the mantle xenoliths entrained alkaline rocks represent an early alkaline intrusive activity preceding the main Deccan volcanism. The closely corresponding ages of the alkaline rocks and tholeiite rocks of the DVP suggest a limited period of plume incubation. These studies have brought out the necessity of re-examining the field, petrographic, and geochemical aspects of most of the alkaline complexes which are situated to the north of the main DVP.

Occurrences of alkaline-carbonatite complexes, spatially and temporally related to the major CFB provinces world over have been useful in analyzing the plume-lithosphere interaction. The alkaline magmatism from the Kutch region provides an appropriate dataset to explore the processes of chemical evolution of the Sub Continental Lithospheric Mantle (SCLM) as these rocks contain xenoliths of mantle rock types. A primary concern is centered on whether the host alkaline rocks have been derived from the metasomatically enriched subcontinental lithospheric mantle (Gallagher and Hawkesworth, 1992; Turner et al., 1996; Gibson et al., 1996) or sub-lithospheric sources in the asthenosphere (McKenzie and Bickle, 1988; White and McKenzie, 1989; Arndt and Christensen, 1992) or from upwelling mantle (plumes?). The previously generated data on the xenoliths and the data generated during the present study can provide insights into important issues such as magma source regions, infiltration and metasomatic modification of the SCLM and the relative contributions from the SCLM and the upwelling mantle (plume?) in the generation of
alkaline magmatism in this region. Besides, the temperature and pressure data obtained for the ultramafic xenoliths can be compared with the geophysical data available in the area of investigation. This would enable to understand the nature, structure and overall evolution of the deep continental crust in this part of India.

1.9 Objectives of the study

The following objectives have been defined for the present study:

1. Classification of the alkaline host and xenoliths based on the mode and bulk chemistry.
2. Based on petrography and mineral chemistry comment on the petrogenetic aspects of the ultramafic xenoliths.
3. Based on the mineral chemistry, determine the P-T conditions of the various xenoliths and infer the geothermal gradient.
4. Comment on the nature of the upper mantle beneath the DVP as deduced from the xenoliths.
5. Characterize the probable nature of source for the alkaline rocks (plugs/dykes/flows) from Kutch in particular and the DVP in general.

1.10 Method of study

The methodology adopted during the course of this study included:

1. Library work: Exhaustive literature survey of the topic of investigation was undertaken. Published papers were collected from libraries of University of Pune, Macquarie University, Sydney, etc. Besides, relevant literature was obtained through the Internet.

2. Preparation of base map: The 1:25,000 scale base map was prepared by making use of the Survey of India toposheets available at the Department of Geology, University of Pune. The outcome of the literature survey was used in delineating important locations exposing igneous intrusions. This helped define the boundaries of the study area. Detailed maps were then prepared on 1:50,000 Sol toposheets made available by the Department of Geology, M.S. University, Baroda and ‘Sahajeevan’, Bhuj - a leading NGO working on Watershed Development in Kutch.
3. **Geological mapping and sampling:** The base maps prepared were used in the field to prepare the detailed geological maps in the field. The field work of not less than 70 man days (9 field trips) were undertaken. Mapping of 18 alkaline plugs, 2 sills, 24 dykes and 4 lava flows was undertaken. The geological map on 1:50000 scale has been prepared. Representative samples of the xenoliths and alkaline rocks from plugs, sills, dykes and flows were collected for petrographic and geochemical analyses.

4. **Laboratory work:** This included the preparation of thin sections of selected samples to undertake petrographic studies. Detailed studies of the texture, mineralogy and modal analyses were undertaken for the xenoliths and host rocks. On the basis of petrography, samples were chosen for the determination of major, trace elements and REE content. The facilities at Department of Geology, University of Pune, and GEMOC, Macquarie University, Sydney, Australia were availed.

5. **Synthesis of the data, thesis writing and submission:** The data generated during the field, petrographic and geochemical studies were synthesized, interpreted and are produced in this thesis.