Chapter 6

Synthesis and Discussions
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6.1 Xenoliths as windows to the mantle processes

Reconstruction of a geologically realistic model for the nature of the crust and upper mantle involves combined assessment of both petrological and geophysical data. The petrological studies of xenoliths that are accidentally brought to the surface during volcanism aid in understanding the physical characteristics such as density, magnetic, seismic properties, etc. and help constrain the temperature and pressure conditions at the time of entrainment. Thus, xenoliths of different origin provide samples of deep-seated, inaccessible parts of the Earth and reveal vital information that supplement indirect information deciphered from geophysical studies. In other words, it is possible to attempt 3D lithosphere mapping (O’Reilly and Griffin, 1985) and establish the general stratigraphy of the Earth’s interior, besides aiding the precise location of the crust-mantle boundary (CMB). The xenoliths also aid in understanding the origin and evolution of the lithospheric mantle. The mantle xenoliths from Kutch along with the host alkaline magmatism can shed light on the nature of lithosphere beneath the western part of India. This chapter therefore deals with the synthesis of the field, petrographic and chemical data generated during the course of this investigation based on which the inferences drawn are discussed. The field, petrographic and chemical characters of the mineral phases has already been dealt in great details in the previous chapters. However, for ready reference the salient aspects of these are recapitulated here.

The xenoliths entrained in the melanephelinite-basanite from Kutch are of spinel peridotite type. Most xenoliths range in diameter from 1 to 2 cm; xenoliths 4 to 5 cm in diameter are recorded from Bhujia, Dhrubiya, and Sayala Devi. The xenoliths vary in shape from rounded to sub-rounded and elongated and are mostly granular. At Bhujia and Lodai, the xenoliths are concentrated in the central portion of the sheet-like intrusion, while at Dhrubiya and Sayala Devi they occur mainly at the lower levels of the plugs (Krishnamurthy et al., 1989). As already mentioned, the relatively small size of the xenoliths preclude the whole rock analysis and hence individual minerals were analyzed for their major, trace and REE content. Olivine, orthopyroxene (opx), clinopyroxene (cpx) and spinel in their order of abundance dominate the mineralogy of xenoliths. The olivine content varies between 50 and 60 %, opx between 15 and 20 % and cpx between 2 and 13%.
reddish brown aluminous spinel ranges from 0.5 to 4 %. The spinel peridotites typically are fine grained (0.5 to 2 mm) and unfoliated, and are of Type-1 (Cr-dipside-spinel) lherzolites (Wildshire and Shervais, 1975; Frey and Prinz, 1978). They exhibit mostly protogranular (Mercier and Nicolas, 1975) or xenomorphic granular (Harte, 1977) textures. However, a few samples from Sayala Devi are coarse grained with weakly defined planar fabric. Olivine in all samples displays strain shadows and kink bands and in most samples olivine contains trails of fluid inclusions. The cpx occurs mostly as discrete grains smaller than the olivines or opx, and show finely spaced exsolution lamellae of opx. Spinel in the xenoliths are reddish brown in colour and occur in close association with opx and cpx.

The ultramafic xenoliths entrained in the basanites and melanephelinites from Kutch, Gujarat are characterized by low modal clinopyroxene (rarely exceeding 10 %), orthopyroxenes (between 15 and 20%) and high abundance of olivines. Progressive partial melting of peridotite at mantle pressures changes the phase assemblage of residual rock from ol + cpx + sp through ol + opx + sp to ol. Clinopyroxene is expected to be exhausted when the residual rock contains 60-80% of modal olivine depending upon the initial rock composition and pressure (Jaques and Green, 1980). The Mg# of olivines from the xenoliths varies between 89.85 to 92.25 and average 90.88. The range of Mg#, as well as NiO (0.33–0.45 wt.%) and MnO (0.09–0.18 wt.%), is similar to those of olivines from mantle-derived peridotite xenoliths worldwide (e.g. Frey and Prinz, 1978; Xu et al., 1996,1998; Ionov et al., 1998). Ni content of olivine and the Ni/Co ratio shows a general positive correlation with mg# (Fig 4.4 a). The Ni/Co ratio varies from 19.55 to 21.9, and is in close correspondence with the chondritic value of 21.9 (Anders and Gresvesse, 1989). The Mn and Zn contents of the olivines show good positive correlation with FeO content while the Ni content correlates inversely with FeO; and the Cr correlates negatively with Mg#, suggesting an overall control of partial melting (OReilly et al., 1996).

The orthopyroxenes, like olivines, also show a limited variation in composition, with Wo48.2-49, En4.8. The Mg# varies from 90.28 to 93.16, which are similar to those of the coexisting olivines implying complete chemical equilibrium between the two phases. The Al2O3 contents are relatively low, varying between 3-3.5 wt.%, some of these orthopyroxenes contain exsolved spinel. The Al2O3 content gets negatively correlated with the Mg# and the TiO2 content of the orthopyroxene which is consistent with the process of partial melting. The Al2O3 content of the orthopyroxene is also positively correlated with the Al2O3 of the coexisting spinel (Fig. 4. 6c). This is consistent with the observations of
Sachtleben and Seck (1981) that the abundance of Al in orthopyroxene is not simply a function of temperature but reflects an underlying control by the composition of the coexisting spinel. The orthopyroxenes have low contents of the REE. The Ni/Co of orthopyroxene is relatively constant at ~10 to 13 which is similar to the ratios reported in orthopyroxene of xenoliths from Mt. Shadwell in eastern Australia (Norman, 1998). It is interesting to note that like the Kutch xenoliths, the Mt. Shadwell xenoliths also have a similar narrow temperature range of 860-925°C. In the Primitive Mantle normalized diagrams, the orthopyroxenes display a positive Ti anomaly and in majority of the cases a negative Sr anomaly. The positive Ti anomaly is consistent with the presence of Ti-rich phases such as rutile, observed as exsolution features at least in some samples. The cpx shows relative enrichment of Sr, Ce and in some cases La, Nb, U and Th.

The clinopyroxenes in the xenoliths are typically chrome diopside and have compositions WO_{27.40} EN_{48.40}. They are more enriched in Al_2O_3 than the orthopyroxenes. The Mg# varies from 91.52 to 98.45 and displays a well-defined correlation with those of olivines. The Cr_2O_3 content (0.67 to 1.29 wt. %) behave sympathetically with the Mg#. The CaO content in clinopyroxene varies from 18.24 to 23.98. It has been observed that the MgO content in cpx decreases with increase in the Al_2O_3 content in clinopyroxenes, which is consistent with the melt depletion models. It is also noticed that there is a wide scatter of points, which may be attributed to varying degrees of partial melting or the scatter may be attributed to the variability of Fe at a particular value of Al. The decreasing Al content of the clinopyroxenes with increasing Cr/Cr+Al of the spinel is consistent with a primary compositional control by partial melting. The CaO however does not define a clear trend in the clinopyroxenes from the present study. The FeO content in clinopyroxenes plot in a restricted range and generally exhibit a positive correlation with Al_2O_3. The TiO_2 content in clinopyroxenes is positively correlated with the Al_2O_3 content. However, some samples have higher values indicating that some other processes have added TiO_2. Thus the major element content of clinopyroxene reflects an overall control by partial melting. Amongst the trace elements in cpx, Ni and Co are positively correlated with MgO while the V content shows negative correlation with MgO (Fig. 4.10). The element Sc does not show a expected positive trend with that of MgO and the discrepancy can be attributed to the greater incompatibility of Sc at higher degree of partial melting as clinopyroxene diminishes (low modal abundance) from the residue (Griffin et al., 1999). Ce contents decrease with increasing Mg# (Fig. 4.11d). A similar trend has been recorded by Johnson et al. (1990) and
has been ascribed to the process of partial melting. However, in the Kutch xenoliths, the Ce values are 100 times more than those described by Johnson et al. (1990), and the enrichment of Ce relative to the HREE is not consistent with the partial melting process.

In the Primitive Mantle normalized trace element and REE diagram most of the clinopyroxenes exhibit deep negative Ti and Nb anomalies, and shallower Zr anomalies. In some samples, Sr anomalies are also seen. Most of the cpx exhibit moderate to flat HREE patterns and moderately to highly depleted middle REE. The highly incompatible elements such as the LREE however exhibit a contrasting behaviour. The highly depleted sample (DB-SD17) exhibits a moderately enriched incompatible element pattern, with relative enrichment in U, Th, Nb and LREE. Most of the samples show strikingly higher concentrations of the most incompatible trace elements, and this relative enrichment extends at least to the middle REE; several samples show negative slopes extending even into the HREE.

Spinel displays a wide variation in composition from Al-rich to moderately Cr-rich (Cr# 24.05 to 74.39) varieties. Generally, the low TiO₂ concentrations (0.01 to 0.61 wt.%) in the spinels is suggestive of the residual nature of the samples. The composition of residual phases in peridotites changes continuously with the degree of partial melting i.e. Al contents of spinel decrease with increasing degree of partial melting whereas the Cr of spinel generally increases. Therefore, Cr/Al ratios (or Cr#) of spinel could be used as an indicator of the degree of partial melting (e.g. Song and Frey, 1989; Dick and Bullen, 1984; Hellebrand et al., 2001). The spinels from the xenoliths of Kutch resemble those from abyssal peridotites. The spinel compositions also indicate that the xenoliths experienced variable degree of partial melting i.e. one set of xenoliths experience low degrees (<5%) partial melting while few samples underwent higher degrees (>10%) of partial melting.

The mineralogical and the chemical characters discussed make it clear that the xenoliths in general and minerals in particular represent residues of various degrees of partial melting of the upper mantle. To constrain the amount of partial melting various models were used in the present study. Frey et al. (1985) and Prinzhofer and Allegre (1985) used trace elements in clinopyroxenes to model melting conditions in alpine peridotites. Johnson et al. (1990) used primary Ti and Zr contents in clinopyroxenes to model melting in abyssal peridotites. Subsequently, Norman (1998) and Xu et al. (2000) modeled melting in intra plate mantle derived xenoliths. However, they used more compatible elements like Y and Yb to negate the effects of metasomatic mobility of Ti and Zr. Karmalkar et al.,
(1999; 2000) attempted modeling of the Kutch xenoliths by using the criteria of Norman (1998) and Xu et al. (2000). Modeling of a primitive source was attempted for batch and fractional melting separately. The results clearly shows that the Y and Yb concentration for the dipoles from the spinel lherzolite xenoliths follow the predicted melting trends. In the fertile xenoliths the concentration of the more compatible elements like Y and Yb can be produced by 2 to 5% melting of the primitive mantle source. For such low degrees of melting, the HREE concentrations are insensitive to the style of melting i.e. batch or fractional melting. However, the highly depleted samples require a high degree of batch melting (45-50%), but will require only 10 to 15% of fractional melting. This is consistent with the overall behavior of major and trace element concentrations in co-existing olivine, clinopyroxene, orthopyroxene and spinel that show element correlations with Mg# and Cr# expected from progressive extraction of partial melt from the mantle (Karmalkar et al., 2000). However, the highly incompatible elements viz. Nb, Zr, Ti and most of the LREE exhibit large scatter and do not follow the predicted melting trend suggesting addition of these elements to the already depleted peridotites by some other process, possibly by metasomatism. The data presented above indicates that the mantle beneath Kutch may have been subjected to moderate to high depletion, with possibly an earlier event of wide spread cryptic metasomatism.

Recently, numerous studies have emphasized the importance of metasomatism as an essential precursor to alkaline magmatism. H$_2$O- and CO$_2$- rich fluids as well as basaltic-, carbonatitic and silicic melts are considered potent agents causing different types of mantle metasomatism. Mantle xenoliths from different localities show extensive evidence of pervasive metasomatism by the modal presence of hydrous minerals (modal metasomatism) or enrichment in incompatible elements alone without the development of any hydrous minerals (cryptic metasomatism). As already stated, the Kutch xenoliths are devoid of hydroxyl bearing mineral phases. It has been demonstrated that the variation in the major, trace and rare earth elements of individual mineral phases within the Kutch xenoliths, are mostly controlled by the process of partial melting. Although the low concentrations of HREE and some MREE, can be attributed to the low degrees of partial melting, the abnormally high concentration of LREE and many MREE cannot be simply explained by the melting process alone. Th, U, Nb, Sr, Zr and LREE enriched nature of the clinopyroxenes imply addition of these elements. Petrographic observations such as neoblasts of olivine, opx and cpx armoring the large porphyroclasts of olivine and opx are
some times seen. Occurrence of such neoblast has been attributed to in situ heating and metasomatism during magmatism in the xenoliths from Canary Island (Neumann, 1991; Wulff-Pedersen et al., 1999). In general, the style of metasomatism beneath Kutch is therefore cryptic (Karmalkar and Rege, 2002). During the process of cryptic metasomatism, Zr was fractionated from Hf leading to high Zr/Hf ratios in some samples. Besides this, the metasomatic processes also added considerable amounts of Fe as is documented by the negative correlation between Mg# and Ce.

The partial melting models demonstrate that metasomatizing fluids were capable of adding Zr and Nb, but apparently did not significantly affect the Ti contents of clinopyroxenes. Even in the highly LREE-enriched samples, the negative HFSE anomalies persist, suggesting that the HFSE anomalies within the clinopyroxenes are the result of 'pre-metasomatic' depletion in these incompatible elements (Ionov et al., 1993; Rudnick et al., 1993). The strong depletion in Zr-Hf and Ti relative to REE found among clinopyroxenes in the Kutch xenoliths is generally regarded as strong indicator of carbonatite metasomatism. Carbonatite melts have very low viscosities and may be effective agents for transporting incompatible elements in the upper mantle and thus are important in controlling the incompatible trace element budget in the lithospheric mantle.

Since Nb has low solubility in hydrous fluids (Kepler, 1996) the enrichment of Nb in the Kutch samples is considered as evidence against the role of water or hydrous fluids as the metasomatizing agent. Green et al., (1992) have shown that the Nb partitions strongly into a carbonatite melt co-existing with a silicate melt, and highly LREE enriched carbonatite melts can show pronounced negative anomalies of HFSE relative to REE, because of fractionation and removal of potential carrier minerals (e.g. sphene, perovskite and zircon) of HFSE.

Strontium enrichment has been regarded as a consequence of trace-element exchange between a carbonatite medium and the peridotite minerals, especially clinopyroxenes (Ionov et al., 1993). The Zr/Hf ratio of some samples (DB-D1, DB-D12 and DB-DD9) is anomalously high and has been attributed to carbonatite-related mantle metasomatism (Dupuy et al., 1992). Hf is believed to be partitioned more strongly into the silicate melt than Zr, leading to higher Zr/Hf ratios in co-existing carbonate melt (Hamilton et al., 1989). Although no carbonate has been recorded in the xenoliths, glass patches are common and this glass is generally enriched in silica, alumina and/or alkalis. Such glasses
have been interpreted as products of reaction between mantle rocks and carbonate rich fluids (Ionov et al., 1994; Karmalkar and Sarma, 2003).

The geochemical characteristics of mantle-derived carbonatites include high La/Yb, Zr/Hf and Ca/Al ratios and low Ti/Eu ratios. It has been pointed out that these ratios are not individually unique to carbonatite melts, but together provide evidence for carbonatite metasomatism. Comparison of natural carbonatite compositions with silicate melt compositions such as OIB shows carbonatites to be enriched in La, Ce and Sr and depleted in Hf and Ti. Carbonatite melts may remain in equilibrium with their mantle host by the reaction:

\[
\text{CaMg(CO}_3\text{)}_2 + 4\text{MgSiO}_3 = \text{CaMgSi}_2\text{O}_6 + 2\text{Mg}_2\text{SiO}_4 + 2\text{CO}
\]

Dolomite orthopyroxene clinopyroxene olivine fluid

Such carbonatite melts have generally been regarded as ‘ephemeral’. The above reaction produces metasomatic clinopyroxene at the expense of orthopyroxene changing lherzolite to wehlrite. However, the Kutch xenoliths are mostly of lherzolite-harzburgite type with very low abundance of modal clinopyroxene, and wehlrites sensu stricto are absent. The absence of cpx-enriched wehlrites may be attributed to the low fluid/rock ratio or absence of a carbonatite metasomatising fluid. In the absence of isotopic and radiometric data, the exact timing of the metasomatic event is on the Kutch xenoliths difficult to constrain. However, based on the chemical characteristics of both the xenoliths and the host alkaline rocks as well as the textural features of the xenoliths, certain inferences can be drawn. The primary minerals in the xenoliths are in textural equilibrium. The individual mineral grains in all the xenoliths analyzed are unzoned with respect to trace elements, indicating pervasive homogenization of the metasomatic signature. Hence, the enrichment is an upper mantle event and cannot be linked to the alkaline magmatism that brought them to the surface. This implies that the metasomatic fluid interacted with the peridotite at relatively low temperatures in the lithospheric mantle. The calculated low equilibrium temperatures and pressure estimates support this contention.
6.1.2 Xenoliths as shallow ‘SCLM’?

Low equilibrium temperatures (884-972°C) of the xenoliths may indicate entrainment of spinel peridotite xenoliths from shallow depths within the lithosphere. The absence of both plagioclase and garnet in the xenoliths constrains the pressure limit between -10 and -20 kbar respectively. These estimates are consistent with the Al/Cr ratios in the spinels, which indicate a pressure of 12-15 kbar. Referring the temperatures to the geotherms typical for areas of alkali-basalt volcanism, such as the one derived for the Tertiary volcanic areas of southeastern Australia (O’Rielly and Griffin, 1985), yields pressure estimates of 9 to 12 kbar (27 to 38 km depth). The approximate pressure estimates vary between 12 and 15 kbar (38 to 45 km depth) when the temperatures are referred to the xenolith based geotherm from Saudi-Arabia (Mishwat and Nasir, 2004). Do the Kutch xenoliths then appear to represent a shallow young juvenile sub-continental lithospheric mantle created during the Jurassic-Cretaceous rifting?

6.1.3 Xenoliths - Young Juvenile Mantle versus Cratonic Mantle?

The continents of the world are cored by Archaean cratons that are underlain by seismically fast mantle roots descending to depths of >200 km (Jordan, 1988). These roots appear to be both colder than the surrounding asthenospheric mantle and are very old (Pearson et al., 1995). The old ages (>2.5 Ga) raise questions of their origin and long-term stability. If it is true that cratonic mantle roots have the same composition as the surrounding asthenospheric mantle, then their lower temperatures should render them unstable. Jordan (1988) was the first to recognize that the long-term stability of continental roots might reflect their depleted composition relative to asthenospheric mantle. Archaean SCLM or the Cratonic Mantle is distinctly different from younger mantle. Archaean SCLM is highly depleted, commonly strongly stratified and contains subcalcic harzburgites, that are essentially absent in younger SCLM (Griffin et al., 2003). The ultramafic xenoliths entrained in the melanephelinites and basanites from Kutch are characterized by low modal clinopyroxene (rarely exceeding 10%), orthopyroxenes (between 15 and 20%) and high abundance of olivines. In the classification based on modes, the xenoliths from Kutch define two populations, one mostly of lherzolite and the other of harzburgite + dunite. There is a distinct difference in mineral compositions between the two populations of xenoliths. The dunite and harzburgites are highly refractory (Mg# > 92) and are similar to the olivine
rich xenolith suites from Archaean mantle world over (Bernstein et al., 1998; Bernstein and Brooks, 1999). Contrary to these depleted xenoliths, the other population, mostly of lherzolite, is comparatively fertile. The mineral composition of such fertile lherzolite shows them to be moderately depleted when compared to the primitive mantle, with high CaO and Al₂O₃ contents and Mg# < 92. Xenolith samples from Kutch (e.g. DB-X2, DB-D1 and DB-B2) have a relatively high and flat HREE patterns and moderately depleted middle REE, while the most depleted sample (DB-SD17) shows low HREE and middle REE. Both the populations, however, show unexpectedly moderate to high abundances of LILE and LREE and negative anomalies in Zr, Nb and Ti. One of the unique features of Cratonic Mantle is that it is dominated by high Mg# (91-94) harzburgitic peridotite i.e. olivine- and orthopyroxene dominated lithologies (Boyd and Mertzman, 1987; Boyd, 1989; Boyd et al., 1993, 1997; Rudnick et al., 1994; Bernstein et al., 1998, 2006; Griffin et al., 1999; Hanghoj et al., 2000; Pearson et al., 2003). Cratonic peridotites are impoverished in clinopyroxene, Ca, Fe, and Al compared to fertile asthenospheric mantle and Phanerozoic peridotites, which are lherzolitic in composition (i.e. containing 10 to 20% clinopyroxene), have lower Mg# (88-89 for fertile asthenosphere and 88-91 for Phanerozoic peridotites), and have higher Ca, Fe and Al.

The xenoliths from Kutch have yielded low equilibrium temperatures of 884-972°C. The silicate minerals are typically depleted in the fusible basaltic components viz. Al, Fe and Ca. In contrast to their depletion in incompatible major elements, these xenoliths show unexpectedly high abundances of LILE and LREE. This is an artifact of the complex history of melt extraction i.e. depletion and enrichment that the cratonic lithosphere has undergone. Highly depleted xenoliths (recording low equilibration temperatures and pressures less than ~2 GPa) characterised by low modal clinopyroxene, high Mg# > 92 with moderate to high opx content are recorded from many cratonic regions viz. Kaapvaal craton in southern Africa, Slave craton, Northwest Territories, Canada, etc. The depletion in clinopyroxene, Ca, Fe and Al in cratonic lithosphere relative to the asthenospheric mantle is most likely due to large degrees of melt extraction. It has been suggested that high Mg# peridotites of cratonic mantle were residues of mantle melting (e.g. O’Hara et al., 1975; Boyd and Mertzman, 1987; Takaishi, 1990). Comparisons with partial melting experiments (Walter, 1998; 1999; Herzberg, 1999; 2004) imply that the cratonic mantle peridotites are the product of 30-50% melt extraction.
In general cratonic mantle xenoliths can be sub-divided into two textural groups (Boyd, 1987), granular type and sheared or porphyroblastic type. Both these types have distinct textures, equilibration temperature and pressures as well as chemical characters, which set them apart from each other. The granular type peridotites have lower equilibration pressures and temperatures (lower than 5.5 GPa and 1200°C) and are highly melt depleted. On the contrary, the sheared or porphyroblastic type and have equilibration pressures and temperatures exceeding 5.5 GPa and 1200°C. These are more fertile, some approaching the fertility of asthenospheric mantle. The transition (150-175 km) between the two groups, most likely defines the base of a more depleted mantle root, which is the chemical boundary layer.

When the modal abundance of olivines is plotted against the Mg#, depicting the relationship between melt depletion and residual peridotite composition, the spinel peridotite xenolith from Kutch plot above the oceanic trend of Boyd (1989) and show considerable scatter without defining any specific trend (Fig. 4.1a). The oceanic trend in the figure is the compositional trend from fertile lherzolite to depleted harzburgite defined by lithosphere forming processes in orogenic belts and ocean basins (Boyd, 1989). However, it is to be noted that very few samples plot in the Phanerozoic field, while most of them occupy the Proterozoic and Archaean fields (Fig. 6.1a). The Mg# in olivine thus defines two populations, one below 91, while the other greater than 91. The xenolith suites from the Kaapvaal craton in South Africa has long been considered to represent typical examples of cratonic mantle. When the Kutch xenolith data is plotted in the Cr# in spinel versus modal olivine diagram they show considerable scatter, but most samples plot well within the field demarcated for the Kaapvaal craton (Fig. 6.1b). This indicates that at least some of the xenoliths from Kutch may represent the cratonic mantle.

A subset of relatively orthopyroxene-poor Kaapvaal harzburgite xenoliths reflect some 30% decompression melting at 4-5 GPa (Herzberg, 2004). About 30% of continental upper mantle samples are enriched in opx/olivine relative to peridotites residual from partial melting of the primitive mantle. The best-known suites from Kaapvaal craton, especially the ‘low temperature’ spinel and garnet peridotite xenoliths have high modal orthopyroxene. For the majority of Kaapvaal peridotites, however, their high modal orthopyroxene contents render them difficult to relate directly to melt extraction processes (e.g. Kesson and Ringwood, 1989; Boyd, 1989; Kelemen et al., 1998). The high opx modal contents (or equivalently high SiO₂ content) for these highly melt depleted harzburgites suggest that

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either silica has been added or their initial starting compositions were Si rich to begin with. It is largely assumed that the latter is not the case and, as such, most debates have centered on finding a mechanism to explain the Si enrichment. Various hypotheses have been proposed to explain opx enrichment in high Mg# cratonic mantle samples. These include:

(a) High degrees of melting at relatively high pressure producing a high Mg# residue with high (>25%) opx. Subsequently, metamorphic differentiation creates peridotites with higher and lower opx from the residues (Boyd, 1989).

(b) High Mg# peridotites with low opx (<25%) created by high degree of melting at low to moderate pressure, and melt/rock reaction may have subsequently added SiO2 to create high opx peridotites (Kesson and Ringswood, 1989; Kelemen, et al., 1992; Rudnick et al., 1994; Kelemen et al., 1998; Walter, 2003, Pearson et al., 2003; Lee et al., 2003)). This is a two-stage process in which dunitic or orthopyroxene poor harzburgite residues from high degree of melt extraction underwent Si addition perhaps by reaction with SiO2-rich melts originating from subduction zones.

(c) High Mg#, cratonic mantle peridotites with 30 to 50 wt.% opx as mixtures of ~50% high Mg, low opx residual peridotites (as in the hypothesis b) + ~50% high pressure igneous cumulates with 25% olivine and 75% opx (Herzberg, 1993; Arndt et al., 2002) i.e. these are linked to crystal fractionation processes in an Archaean magma ocean.

While the orthopyroxene-rich nature of high Mg# peridotite xenoliths from southern African and Siberian cratons was long considered typical of shallow cratonic mantle, over the past decade, high Mg# peridotite xenoliths with low modal orthopyroxene (<20%) have been reported from the Tanzanian-, Greenland-, and Slave cratons (Rudnick et al., 1994; Bernstein, et al., 1998, 2006; Kopylova and Russell, 2000; Bizzarro and Stevenson, 2003). These are described to have an origin as a shallow residue from ~ 40% polybaric decompression melting in the Archaean (Bernstein et al., 1998, 2006; Hanghej et al., 2000). The presence of such orthopyroxene-poor residues in xenolith suites lends credence to the existence of such a protolith beneath cratonic mantle. The xenoliths from the present
Figure 6.1. (a) Mg# in olivine vs. modal olivine in volume percent for Kutch peridotite xenoliths. Field for Wiedeman Fjord, eastern Greenland after Bernstein et al., (1998) and Ubekendt, Ejlund, west Greenland from Bernstein et al. (2006). Compositional fields for mantle peridotite from Archean cratons (xenoliths) and Proterozoic and Phanerozoic origins (xenoliths, orogenic massifs, ophiolites and abyssal peridotites) after Boyd (1989) and Menzies (1990) (b) Cr# spinel vs. modal olivine for Kutch peridotite xenoliths. Fields for Kaapvaal from Hervig et al. (1980), Boyd et al. (1999) and Tanzania from Lee and Rudnick (1999).
investigation have low orthopyroxene content (between 10 and 22%) and similarly indicate an older cratonic protolith beneath Kutch.

Bernstein et al. (1998) by adopting a simple mass balance calculation have shown that the depleted Wiedemann peridotite suite from eastern Greenland could form by extraction of ~ 40% melt from pyrolite mantle leaving a residue with olivine Mg\# of 92.7. For a compilation of global suites of cratonic, coarse, Mg-rich, “low-temperature” peridotites (mostly harzburgites), Pearson et al. (2003) found average olivine Mg \# of 92.8. This compilation includes both spinel and garnet peridotites. Bernstein et al. (2007) argue that the consistent olivine Mg\# in cratonic mantle reflects Archaean mantle melting to the exhaustion of orthopyroxene. In the melting experiments it is observed that, the residual orthopyroxene is exhausted at 40-50% melting, with residual olivine Mg\# from 92.8 to 93.5. The interval for orthopyroxene is shown to be much more tightly constrained at 40-42% melting with olivine Mg\# from 92.8 to 93 - if one excludes experiments with more than 45% melting at 6-7 GPa from Walter (1998). Orthopyroxene exhaustion would cause an increase in solidus temperature of the residue by several hundred degrees Celsius, and hence no further melting can occur, without fluxing the residue at very high temperature or increasing the pressure dramatically, inhibiting further increase in Mg\# after orthopyroxene exhaustion (Bernstein et al., 2007).

In the Mg\# of olivine versus Cr\# of spinel diagram, the Kutch xenoliths plot close to the partial melting curve and in general indicate 10 to 15% melting (Fig. 6.2). Most of the xenoliths plot within, or close to, the olivine-spinel mantle array (or residual peridotite array) defined by Arai (1992), and is characterized by low (< 10%) melting. However, few samples plot out side the olivine-spinel mantle array and may be related to higher degrees of partial melting (10 to 25%) closely comparable to the oceanic supra-subduction zone peridotites. This is consistent with limited range of Mg\# in olivine (91-92.5) and lower or orthopyroxene poor character (mostly < 20%) of the xenoliths.

Kelemen et al. (1998) have demonstrated that the opx enrichment (or equivalently high SiO\_2 content) in the previously depleted peridotite protolith is the result of melt/rock reaction. The Ni content of olivines increases with increase in modal percentage of orthopyroxene. This positive correlation between Ni of olivine and modal opx content forms the basis for their hypothesis. According to Kelemen et al. (1998), partial melting at ~ 30 kbar, close to the transition between garnet and spinel Iherzolite stability fields, produces slight enrichment in opx in residues up to the point at which cpx and garnet are exhausted,
where modal opx is ~ 30 wt.% after which opx will be progressively depleted by continued melting. Until opx is exhausted, Ni contents in olivine drops with increasing modal opx. After opx is completely exhausted, Ni in olivine is relatively constant. Thus, melting models produces neither a correlation between Ni in olivine and modal opx, nor > 30% modal opx as has been observed in some Kaapvaal xenoliths. Boyd (1997) accounted the higher opx modal content in the Kaapvaal xenoliths to metamorphic differentiation plus cooling of high pressure residues. Metamorphic differentiation, by itself, will not produce substantial variation in phase compositions. However, if metamorphic differentiation occurs at high temperature, where opx is relatively rich in Ni, and then the rock cools, Ni must diffuse from opx in to olivine in order to maintain equilibrium. Cooling of an opx-rich rock increases Ni in olivine more than cooling of an opx-poor rock, giving rise to a positive correlation between modal opx and Ni in olivine (Boyd, 1989; Kelemen, et al., 1998). However, this process is insufficient to account for the observed slope of the positive correlation between Ni in olivine and opx (Kelemen et al., 1998). Kelemen and Hart (1996) have noted that the opx rich character of many cratonic xenoliths is consistent with an origin by consequence of melt/rock reactions in which melt1 + olivine forms melt2 + opx, with a net increase in the SiO2 content of peridotite product and so as the positive correlation between Ni in olivine and modal opx. Accordingly, small degree melts of subducted eclogite reacts with depleted, low opx harzburgite to produce high opx harzburgite (+ modified melt). This could occur above a subduction zone, if subducted oceanic crust and/or sediment underwent small amounts of partial melting and the melts migrated upward into hotter mantle peridotite (Kelemen et al., 1998 and references therein). Because Ni is enriched in olivine/opx at equilibrium, reactions which consume olivine to produce opx will decrease the size of the olivine reservoir for Ni, driving Ni concentration higher in the remaining olivine. Accordingly a positive correlation may reflect SiO2 enrichment of a high Mg# protolith by reactions with small degree silicic melts from subducted eclogite with overlying peridotite (Kelemen et al., 1997).

Looking at the lower modal content of the opx in the Kutch xenoliths, at least few of them can be the product of ~ 25 to 30 % partial melting at lower pressure i.e. ~ 3 GPa. In the Ni of olivine versus modal opx diagram (Fig. 4.1b) the Kutch xenoliths show a very strong positive correlation suggesting a moderate addition of opx and so as the SiO2 content. As already stated that the Kutch xenoliths are enriched in LILE and LREE, which is in contrast

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Figure 6.2. Plot of Cr# spinel vs Mg# olivine from spinel lherzolite xenoliths from Kutch. Fields of abyssal (ocean ridge) peridotites are from Dick and Bullen (1984) while those from oceanic supra-subduction zone (ssz) peridotites and passive continental margin peridotites are from Pearce et al. (1999). The olivine-spinel mantle array and the melting trend are from Arai (1992).
to partial melting models. There is a strong evidence of post depletion modifier although of variable nature in both the sample populations. These xenoliths show unexpectedly high abundances of LILE and LREE and negative anomalies in Zr, Nb and T indicative of metasomatism. The compositional contrast between the two populations pose the problem of how to reconcile the presence of small volumes of relatively fertile material within large bodies of extremely depleted material. A more likely explanation is that the lherzolite (relatively fertile) represent metasomatic re-fertilization of the dunite + harzburgite samples within the mantle (Beyer et al., 2006). The re-fertilizing agent was a melt/fluid rich in Fe, Ca, Al and LREE and low in Ti and Nb similar to the eclogitic magmas this is in contrast to the carbonatite metasomatism as envisaged before (Karmalka and Sharma, 2003). The positive correlation between Ni contents of olivine and moda proportions of opx in mantle xenoliths indicate reaction between SiO2 rich liquids or small degree of melts/fluids originating from subduction zones (Kelemen et al., 1998; Walter 2003; Lee et al., 2003). The observed equilibration temperatures are only slightly hotter than a conductive continental geotherm at 40 to 90 km depths, rendering it unlikely that the xenoliths represent juvenile continental upper mantle created during the Jurassic-Cretaceous riftting as was previously envisaged. The various geochemical features observed makes the Kutch xenoliths probable residues of high degree of melting during the Archean and suggests the presence of colder and therefore older Archean mantle roots, hitherto unreported, beneath the Kutch region.

6.2. Lamproite-Melanephelinite-Basanite the "deeper" SCLM

The study area from Kutch contains a variety of igneous rock types such as lamproites, melanephelinite and basanites, the later beings host to the spinel peridotite xenoliths. It therefore becomes imperative to deal with the genesis and evolution of each igneous rock type seperately. The following sub-sections elaborate on these and allied aspects.

6.2.1 Lamproite as probes to the complexly metasomatised ancient cratonic mantle

Lamproites and kimberlites represent the most extreme magmas compositions that reach the Earth's surface. Their ultrapotassic nature and variety in modal mineralogy (Mitchell and Bergman, 1991) suggests derivation from a geochemically anomalous mantle (Basu and Tatsumoto, 1979; Kramers et al., 1981). Lamproites are found in diverse tectonic...
settings, most of them seem to be post-tectonic and occur at cratonic margins, while others occur within cratons and in accreted mobile belts. Most reported global occurrences of these rocks are Cretaceous and younger in age. In India, the lamproites and kimberlites (Fig. 6.3) are restricted to the Aravalli-, Singhbhum- and Dharwar craton (Naqvi and Rogers, 1987). Kimberlites and lamproites in these cratons are usually found in clusters and are grouped into respective fields. Although some reports of lamprophyres rocks were reported from the western Aravalli craton (see Rock and Paul, 1989 and references therein), no kimberlitic or lamproitic occurrence has been reported in published literature. Significant is therefore the reporting of the lamproite dykes from Central Kutch in the present thesis. The occurrence of lamproites in Kutch could therefore be used to redefine the new Badi Lamproite field (BLF) and rekindle prospecting avenues in the region.

The SiO₂ content of the lamproites from Kutch is the lowest (37.58 and 38.09 wt.%) in the entire dataset generated in the present study. The lamproites record unusual normative mineralogy with presence of leucite and olivine. The Al₂O₃/TiO₂ ratio of 2.24 (KJb1) and 2.72 (Sk2b) is significantly lower than the melanephelinite-basanite rocks from the present study. Similarly, the TiO₂/P₂O₅ ratios for the Kutch samples are lower than the melanephelinite-basanite from the present study. The sample Sk2b has an Nb/Zr ratio of 0.23 as compared to 0.44 for sample KJb1. The Nb/Zr ratio of 0.23 for the sample Sk2b is similar to that reported for Majhgawan sample (Chalapathi Rao, 2005) and is considered to be close to the olivine lamproite value of 0.20. In the La/Yb ratio vs. Sm diagram, sample KJb1 plots within the world and Indian kimberlite field while sample Sk2b shows kimberlitic affinity (Fig. 5.6b). The average Sc content of ~ 19.3 ppm for the Kutch lamproites is similar to the world average of 19.4 ppm for micaceous kimberlites (Kable et al., 1975). Marshintsev and Sukhneva (1970) and Muramatsu (1983) indicate compatible trace elements are hosted by olivine and spinel and to a lesser extent by perovskite (Sc) and clinopyroxene (Cr, V, Ni). Kimberlites are poor in Zr relative to lamproites that contain >1000 ppm of Zr (Scott Smith and Skinner, 1984; Srinivas Choudary et al., 2007). The Zr and Hf content in the lamproite sample from Kutch are higher than the established mean of 184 ppm and 5.6 ppm respectively for kimberlites. As perovskite is the primary host for Zr and Hf in lamproites, the Zr and Hf variation in the Kutch samples may be attributed to the variations in the modal proportions of perovskite. In fact, perovskite and apatite are the two key minerals that control the rare earth element budget of the lamproite samples from Kutch. The primitive mantle normalized semi-log plot for the two samples from Kutch.
Figure 6.3. Location of kimberlite fields and lamproite in India. Cratonic boundaries modified after (Naqvi and Rogers, 1987). KLF-Krishna Lamproite field, RLF-Ramadugu Lamproite field, NLF-Narayanpet Lamproite field, MKF-Mahbubnagar Kimberlite filed, WKF-Wajrakarur Kimberlite field, MiKF-Mainpur Kimberlite field, TKF-Tokapal Kimberlite field, PDB-Panna Diamond Belt. Note the location of the newly described Badi Lamproite field (BLF).
show striking similarities implying that the coherence may be due to derivation from a similar source. The LREE in both the samples are enriched (KJb1: 343.55 ppm, Sk2h: 171.81 ppm, world average: ~406 ppm) and show steep gradient with respect to MREE and HREE. The LREE enrichment and HREE depletion is similar to those found in kimberlites (Mitchell, 1986). Both samples show prominent Rb and Sm negative anomalies while Sr, Zr and Ti show small positive anomalies. The La/Yb for the Kutch samples varies from 38.24 to 84.73 and La/Sr varies from 5.79 to 7.93. These values are far from the world averages of 125 and 11.54 respectively for kimberlites.

Thus, based on the petrography, major oxide and trace element geochemistry, modal- and normative mineralogy, etc. and in the absence of mineral chemistry and isotopic studies the samples from Kutch can best be classified as lamproites sensu lato. Mitchell (2006) has rightly pointed out that some ultrapotassic rocks are difficult to classify both mineralogically and chemically and the same is true for the Kutch samples. Scott Smith (1995) proposed that all lamproite-like potassic magmas might be considered as a broad group of magmas, which he termed the “Metasomatized Mantle Magmas” (MMM). Mitchell (2006) modified this to “Metasomatized Lithospheric Mantle (MLM) magmas” to reflect the current opinion that lamproite-like potassic magmas are derived primarily from lithospheric mantle. Several workers (e.g. Fraser et al., 1985; Mitchell and Bergman, 1991; Edgar and Mitchell, 1997; Rao et al., 2004) consider lamproites as small volume partial melts from a sub-continental lithospheric mantle source that was enriched by metasomatism prior to melting. Other models, such as that of Murphy et al. (2002), invoke subduction of sediments derived from Archean continents to the transition zone in the mantle. Others like Davies et al., (2006) consider subducted recycled oceanic crust as a source component in the genesis of lamproites.

One of the most contentious issues related to the lamproite genesis concerns whether they are of lithosphere (e.g. Foley, 1992) or sub-lithosphere asthenosphere (e.g. Murphy et al., 2002) derived melts. The geochemical characters of lamproites viz. high Mg#, Ni and LILE abundances and low Al2O3 are suggestive of mantle source regions (Mimejard and Bell, 2006). Low Al, Si and Ca coupled with high Mg, Ni and Cr led many workers to invoke their generation from a major element depleted source i.e. harzburgitic in nature (Bergman, 1987). The presence of cpx-poor spinel peridotite xenoliths (harzburgites) mostly of cratonic origin in the melanephelite-basanite rocks in Kutch further supports this contention. Extreme impoverishment in HREE and low HFSE are also suggestive of source
depletion by preceding melting event (Tainton and McKenzie, 1994). On the basis of isotopic and experimental studies, lamproites are presently considered to be derived by the partial melting of complex ancient metasomatic veins in the lithospheric harzburgites (Foley, 1992; Mitchell, 1995a, b). The low SiO$_2$, high Mg#, low Al$_2$O$_3$/TiO$_2$, high CaO/Al$_2$O$_3$, high TiO$_2$, high Ni, Cr, Th/U and Nb/Th–Nb/U ratios in the Kutch lamproites specifically recognize the need for a metasomatized source in the mantle.

Potassic mafic alkaline rocks are frequently associated spatially and temporally (e.g. Dawson et al., 1985; Gibson et al., 1995b) and occur in tectonic settings related both to mantle plumes and regional extension. In the DVP, the association of potassic mafic alkaline rocks has been variously attributed to mantle plumes and regional extension. This coincidental occurrence has led many to believe that the mantle plume plays either an active or passive role in the genesis of lamproite magma. The protagonist of ‘passive’ role by mantle plume argue that conductive and advective heating of the thick cratonic lithosphere cause melting of only the readily fusible K-rich parts of the SCLM and generate mafic alkaline magmas viz. kimberlites, lamproites and kamaugites (McKenzie, 1989, Thompson et al., 1990; Gibson et al., 1995a). Thus the amount of upwelling, and hence degree of melting by decompression within the plume head, as well as the site and type of magmatism is primarily shown to be controlled by the thickness of the overlying sub-continental lithospheric mantle (McKenzie and Bickle, 1988). In the Zr/Hf vs. Nb/Ta diagram (Fig. 6.4a), the two lamproite samples with chondritic to near-chondritic Nb/Ta ratios from Kutch falls close to the field marked for continental basalts corroborating to their occurrence in the field. However, it is pertinent to mention here that the closest basalt outcrop is almost 80-100 km away. Besides, the lamproites are seen located on the cross-section of the Kutch Mainland Fault and Median high. The Kutch region has been traditionally shown to represent a paleo-rift graben whose evolutionary history dates back to the Mesozoic times. Although at this stage, there is no precise data to constraint the age of emplacement of the lamproites, on the basis of their intrusion into the Chaurio Formation it is envisaged that their emplacement is not coeval with the melanephelinite-basanite and basalts from Kutch, and hence could predate the main alkaline magmatism event. The location of the lamproites along the Kutch Mainland Fault cannot be a meager coincidence that indicates the role of deep penetrating fault system in causing adiabatic decompressional melting of readily fusible K-rich parts of the SCLM at great depths and generating small volume lamproitic melts. Experimental studies (Mitchell, 1995b; Mitchell and Edgar, 2002)
suggest the depth of formation of the lamproite magma occurs at and above the lithosphere asthenosphere boundary, e.g. 150-200 km depending on the thickness of the craton root and can be accomplished with or without invoking a subduction related component. Similarly, Gibson et al., (1995) have suggested a greater depth (more than 150 km) in the generation of mafic potassic magmas viz. kamafugite, kimberlites and lamproites. In the Ce/Y vs. Zr/Nb plot (Fig.6.5a) where the continuous lines represent non-modal fractional melting curves for fertile and depleted spinel peridotite and garnet peridotite (Hardison and Fitton, 1991), the Kutch lamproites falls well above the spinel facies and closely follow the trend for the depleted garnet facies with <0.1 % partial melting. The relatively small volume of the lamproite from Kutch and the occurrences of cryptically metasomatized depleted cratonic harzburgite xenoliths entrained in the alkaline rocks support the low melting model of a cryptically metasomatized ancient cratonic mantle.

6.2.2 Melanephelinite-basanite-alkali basalts: uncontaminated mantle (plume?) derived melts

Magmas with compositions similar to oceanic-island basalts (OIB) have been reported from almost all the major CFB provinces, e.g. Ethiopia (Thompson et al., 1983); British Tertiary Volcanic Province (Thompson and Morrison, 1988; Fitton et al., 1997), Deccan (Mahoney, 1988; Simonetti, et al, 1998; Karmalkar et al., 2005); Siberia (Lightfoot et al., 1993) and Paraná-Entendeke (Gibson et al., 1997; 1999; 2005; 2006). These are widely believed to represent uncontaminated mantle plume-derived melts. However, such uncontaminated OIB-type melts represent only small volume of the total proportion of magma erupted in CFB provinces. This has promoted alternative models to explain the genesis of such OIB-type melts. These invoke:

1. assimilation of melts derived from the crust or veined sub-continental lithospheric mantle by plume derived melts (e.g. Carlsen, 1991; Gibson et al., 1995; 1999; 2005); and

2. large scale melting of hydrous peridotite in the SCLM (Hawkesworth et al., 1992; Turner and Hawkesworth, 1995; Turner et al., 1996).

Models that involve passive role of mantle plumes in CFB genesis require relatively large amounts of heat to be transferred to the lithospheric mantle by conduction from the underlying anomalously hot convecting mantle; such a model has been proposed by some
Figure 6.4. (a) Zr/Hf vs. Nb/Ta in major terrestrial silicate reservoirs indicating a Nb deficit with respect to Ta in the accessible silicate Earth (from Münker et al., 2003). The silicate differentiation line indicates a first order coupling of Nb/Ta/Zr/Hf fractionation in terrestrial reservoirs that is in agreement with the partitioning behaviour of the HFSE. The intersection of this line with the chondritic Zr/Hf ratio defines the Nb/Ta ratio of the BSE. Note the scatter in the Kutch basanites (b) Zr/Hf vs. Nb/Ta in ocean island basalts. Note the decoupled nature of the Kutch samples i.e. Nb/Ta remains fairly constant with variable Zr/Hf. Data source: MORB (Büch et al., 2002), average continental crust (Barth et al., 2000) and chondrite from Münker et al. (2003). The arrow indicates the shift in Zr/Hf and Nb/Ta that results from 30% clinopyroxene fractionation (Pflünder et al., 2007).
Figure 6.5 (a) Zr/Nb vs. Ce/Y for the Kutch samples. The continuous lines are the non-modal fractional melting curves calculated (Hardson and Fitton, 1991) for four mantle compositions. GD- depleted garnet lherzolite, GP- primitive garnet lherzolite, SD- depleted spinel lherzolite, SP- primitive spinel lherzolite. Numbers on the lines refer to percentage of melt. (b) La/Yb vs. Tb/Yb plot for the Kutch samples. Continuous lines are for melting of Fertile Lherzolitic mantle, the contours representing the amount of modal garnet (after Macdonald et al., 2001).
for the Para-Entedeka, CFB (Gallahar and Hawkesworth, 1992; Turner and Hawkesworth 1995; Turner et al., 1996).

The Deccan Traps of west central India- is a large-volume basaltic CFB province of the world. 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, the Mandla lobe in the northeast and Saurashtra-Kutch plateau in the northwest (Fig. 1.1a). The DVP consists predominantly of tholeiite lava flows intruded by acidic, alkaline, carbonatite intrusions and igneous complexes. The Deccan flood basalts have been linked to the Reunion Plume by several workers (e.g. Duncan, 1981, Morgan, 1981, Cambell and Griffiths, 1990). In the regional context of the DVP, several workers have linked Kutch to the Reunion hotspot (De, 1979, 1981; Simonetti et al., 1998, Roy, 2003, Karmalkar et al., 2005). Although the generation of CFBs is believed by many to require elevated mantle potential temperatures (i.e. mantle plumes) and in some cases lithospheric thinning- the actual role of the plume is more debatable; does it only provide a heat source or is it also a major contributing melt source? Plate margin stresses and lithospheric extension associated with the rifting processes may also change the geothermal gradient beneath and can contribute to mantle melting (Gibson et al., 1999). In light of these currently debated hypotheses (e.g. Sheth, 2007) it is attempted to discuss the genesis of the melanephelinite-basanite-alkali basalt from the Kutch region in this section.

The alkali magmatism from the Kutch provides an appropriate dataset to explore the processes of chemical evolution of the SCLM as these contain xenoliths of mantle origin. It is important however, to emphasize that the xenoliths and their hosts contain quite different information about the composition of the mantle. The xenoliths in the continental settings represent mostly samples from the spine lherzolite field of the upper SCLM i.e. ~40 km in case of the Kutch xenoliths. The melanephelinite-basanites which host the xenoliths should naturally have originated at deeper levels. Five plugs i.e. Wehar (KW1), Dhram (KN1), Dinodhar Dongar (KDD), Nanama (KNa1), and Bhujia (KB1) represent melanephelinites in the present dataset, while six plugs i.e. Bharapar (KBh1), Vironi (KV1), Vethon (KV1), Sayala Devi (Ksd1), Dhruviya (KD2, KD7) and Waral (KSk2) and two lava flows, one each from Kotoda (KKo1) and Roha (KMi2) represent the basanites from Kutch. The occurrence of the two basanite flows in the near vicinity basanite plugs could possibly represent monogenetic cones that could have fed the flows. The striking similarity in the petrography, major and trace element geochemistry between plugs and flows supports this
contention. Geochemically, the melanephelinite-basanites rocks are characterized by low concentrations of SiO₂ (41.0 to 43.85 wt. %), but high concentrations of MgO (10.20 to 15.27 wt. %). The total alkalis (Na₂O + K₂O) vary between 3.88 and 5.02 wt. % and occupy the melanephelinite-basanite field in the TAS diagram. Three plugs (KL1, KL2, KL3 from Lodai), and two dykes (KH2 and KH3 from Habai), intrusive into the Habo dome represent the alkali basalt magmatism from Kutch. In general, the Al₂O₃/TiO₂, CaO/TiO₂ and TiO₂/P₂O₅ ratios in the alkali basalts are lower than those for the melanephelinite-basanites from Kutch. However, in most of the variation diagrams, the alkali basalts plot in close proximity to the basanites indicating a close genetic relationship.

In an attempt to decipher the nature of the magma and the tectonic setting in which they were emplaced the data generated in the present study was plotted in the established variation diagrams. All the melanephelinite-basanite-alkali basalt samples plot in the OIB field and confirms that these are not the typical Deccan tholeiite rocks. With Mg# (65-69) and Ni (250 to 350 ppm) contents the melanephelinite-basanite can be considered as primary magmas (Claude and Frey, 1982) suggesting that these are only slightly affected by crystal fractionation relative to their parental magmas.

All melanephelinite samples from Kutch show positive anomalies of Ba, Nb, Sr and Zr. Strong negative anomalies are seen for Th and Pb. No Europium anomaly is seen confirming with the absence of modal plagioclase in the samples. The scatter in the pattern of the trace elements may be primary or reflecting crystal fractionation involving predominantly olivine, clinopyroxenes, but not plagioclase (Simonetti et al., 1998). Based on the high abundances of Nb and low Zr/Nb (2.90 to 5.29) the magmatism is of the OIB type. Similarly, the Ce/Pb (19.28-25.74) and P/Nd (52.18-75.06) ratio for the Kutch alkaline rocks are consistent with the relatively constant values for these ratio reported in OIB (25 ± 5 and 74 ± 13, respectively; Sun and McDonough, 1989). Based on the incompatible element patterns of the alkaline rocks from Kutch, it is possible to divide the samples into two groups. In one group, Rb and K show distinct depletions (e.g. Bhujia, Nakhatrana, Nana and Vethon) while in the other (e.g. Dhruviya, Dinodhar Dongar, etc.) variable enrichment in both Rb and K is noticed. These deviations suggest that the Kutch samples did not acquire their geochemical signatures purely from asthenospheric OIB source but suggest an additional source, possibly similar to the continental lithospheric mantle.
The primitive mantle semi-log plots for the melanephelinites are similar to that of basanites indicating that they may be derived from the same/similar source. However, the prominent Ba anomaly seen in the melanephelinites appears subdued in the basanite samples. Strong negative anomalies are seen for Th, Pb and Hf in basanites. Small Europium anomaly is seen in some samples confirming to the presence of plagioclase-like phases in the basanites. The low SiO₂ content, steep REE patterns and high incompatible trace element abundances in both the melanephelinites-basanites are consistent with small degree melts of an enriched garnet lherzolite mantle sources.

Most of the Kutch melanephelinites-basanites-alkali basalts show a wide range of (La/Yb)₀ and (Tb/Yb)₀ ratios but have low (3.44) and uniform (Yb)₀ contents indicating that the Yb is buffered. This is consistent with variable degrees of partial melting with garnet in the residual phase. The ratio of Tb/Yb varies from 0.56 to 0.85 (av. 0.69) as against that of 0.22 for MORB and 0.49 for OIB suggesting HREE fractionation. Garnet signature is also evident from the conjunction of fractionated HREE and low Y, Sc and HREE contents in magmas with Ni >150 ppm. The primitive mantle normalized ratios of Sm/Yb in the Kutch rocks are 4-6, and these values are consistent with the initiation of melting in the presence of residual garnet (McKenzie and O’Nions, 1991; Eilam, 1992). In the Ce/Y vs. Zr/Nb plot (Fig. 6.5a) where the continuous lines represent non-modal fractional melting curves for fertile and depleted spinel peridotite and garnet peridotite (Hardson and Fitton, 1991), excepting the two basanite samples, all the remaining melanephelinite-basanite samples falls well above the spinel facies and closely follow the trend for the garnet facies. This suggests small degrees (1-2 %) of partial melting in the garnet peridotite facies corresponding to depths between 80 and 100 km. Modeling trace element ratios such as La/Yb vs. Tb/Yb (Fig. 6.5b) indicates that the melanephelinite-basanite-alkali basalts rocks were generated by melting 3 to 8% modal garnet in garnet lherzolite field (Macdonald et al., 2001).

The presence of volatiles such as CO₂, H₂O and F in the mantle rocks is highly significant because these dramatically lower the temperature of the peridotite solidus and control the stability of mineral phases such as phlogopite. Experimental studies indicate that the genesis of K-rich mafic alkalic igneous rocks is controlled by volatiles and the depth of melting (Brey and Green, 1977; Brey, 1978; Wyllie and Huang 1976; Canil and Scarfe, 1990). There is no direct evidence for the role of volatiles in the genesis of the mafic
alkalic igneous rocks due to lack of melt inclusions in the phenocryst phase. However, the olivine and pyroxene phases in the mantle xenoliths entrained by these (melanephelinite-basanite) rocks shows trails of fluid inclusions. The results of experimental studies, nevertheless, indicate that the silica undersaturated nature of these magma types is promoted by melting under CO$_2$-rich conditions (Eggler, 1976; Wyllie and Huang, 1976; Brey and Green, 19975, 1977). The presence of primary calcite in the basanite magmas could hint at the presence of CO$_2$-rich conditions. Canel and Scarfe (1990) examined the phase relations in peridotite-CO$_2$ systems and concluded that the melanephelinites could be derived by partial melting of carbonated peridotite at pressures below 30 kbar.

Positive anomalies of Nb, Ba, K, P and Rb in the mafic alkalic magmas invoke contribution of hydrous minerals (phlogopite) and apatite that have contributed to the petrogenesis of the primary magmas. Melting of amphibole or phlogopite enriches the melt in K and other LILE (Sr, from amphibole and Rb and Ba from phlogopite). The prominent negative anomaly at Sr for all the Kutch samples and the relatively high Na/K in the glasses from the Kutch xenoliths (Karmalkar and Sarma, 2003) negates the presence of amphibole. The trace element pattern discussed above can be related both to variable modal content and consumption of phlogopite during the melting process. The stability of phlogopite is enhanced by high CO$_2$/H$_2$O ratio e.g. at pressures less than 28 kbar and in the presence of high CO$_2$/H$_2$O phlogopite is stable up to 1200°C (Mengel and Green, 1986). The inferred presence of residual phlogopite during the production of Kutch alkali magmas implies source regions located towards the base of the SCLM rather than in the asthenosphere. Class and Goldstein (1997) also emphasized the role of hydrous phases in lowering the solidus temperature sufficiently that results in partial melting from conductive heating of the lithosphere by upwelling thermal plumes/convecting mantle. The high Ba/Nb component seen in the Kutch alkali rocks could be derived from the lower part of the lithosphere. The alkali basalts from the Kutch show close resemblance to the basanites in many respect and hence they are believed to be generated through similar sources as has been discussed for the melanephelinites and basanites.

The high abundances of incompatible trace elements in the melanephelinites and basanites suggest that they have melt contributions from an enriched mantle source. As already stated, the Kutch xenoliths are enriched in LILE and LREE, which is in contrast to partial melting models. There is a strong evidence of post depletion modification of variable
nature. An alternative explanation is that the lherzolite (relatively fertile) represent metasomatic re-fertilization of the dunite + harzburgite samples within the mantle (Beyer et al., 2006). The re-fertilizing agent was a melt/fluid rich in Fe, Ca, Al and LREE and low in Ti and Nb similar to the eclogitic magmas/fluids and is in contrast to the carbonatite metasomatism envisaged before (Karmalkar and Sarma, 2003). The positive correlation between Ni contents of olivine and modal proportions of opx in mantle xenoliths indicate reaction between SiO₂ rich liquids or small degree of melts originating from subduction zones. It is therefore envisaged that the SCLM beneath Kutch have undergone at least two episodes of metasomatism.

The isotopic data for a few samples from Kutch and adjacent area have been compiled and used in the present thesis from published literature (Krishnamurthy et al., 1989; Simonetti, et al., 1998). In Fig.6.6, it is clearly seen that the samples from Dhrubiya and Amba Dongar plot slightly away from the Reunion plume and established mantle array (Fig. 6.5b). In contrast, the isotopic data from the Bhujia hill, is characterized by lower initial ³⁶Sr/⁶⁰Sr (0.70357-0.70396) and higher initial ¹⁴³Nd/¹⁴⁴Nd (0.51281-0.51287) ratios (Simonetti, et al., 1998) and closely correspond to that for Reunion mantle (Fisk et. al., 1988). Peng and Mahoney (1995) have attributed the Nd-Sr isotopic signature to the mixing of the Reunion type mantle with the continental lithosphere. Bell and Simonetti (1996) proposed a two-stage model to explain the formation of East-African carbonatites associated with flood basalts. The model invoked:

i) release of metasomatising agents with HIMU-like signatures from upwelling mantle (plume) source, which in turn metasomatised the sub-continental (EMI-like) lithosphere;

ii) variable degrees and discrete partial melting of the resulting heterogeneous metasomatised lithosphere. However, on the basis of the isotopic composition of some of the alkaline rocks from Deccan alkaline complexes, and comparing them with those for East African carbonatites, Simonetti et al. (1998) denied such a possibility.

Simonetti et al. (1998) have strongly supported the significant involvement of plume type mantle in the generation of Deccan alkaline complexes. Simonetti et al. (1998) suggest a mixed source involving three distinct end members viz. asthenosphere (Indian MORB), enriched (old) continental lithosphere, and Reunion plume mantle in the generation of
Figure 6.6. (a) $^{144}$Nd/$^{148}$Nd and $^{87}$Sr/$^{86}$Sr isotope plot for Deccan and related samples. Source data: Deccan basalt fields (Lightfoot and Hawkesworth, 1988) Bhuj, Mundwara, Ambadongar and Sarnu-Dandali samples (Simonetti et al., 1998), Dhrubiyia and Sisagarh samples (Krishnamurthy et al., 1989). (b) $^{144}$Nd/$^{148}$Nd and $^{87}$Sr/$^{86}$Sr isotope correlation plot, showing the main oceanic mantle components of Zindler and Hart (1986). The mantle array is defined by many MORB and ocean island basalts, and Bulk Earth values of $^{144}$Nd/$^{148}$Nd and $^{87}$Sr/$^{86}$Sr can be observed from this trend (Faure, 1986, 2001; Dickin, 1995).
Deccan alkaline magmatism. The La/Nb ratio in the Kutch lavas is less variable (0.60 to 0.80). This range agrees well with the average value of 0.68 for plume related OIB (Gibson et al., 1996) and similar to the 0.69 value for the Reunion (Fisk et al., 1988). Our data on the Kutch samples indicate an OIB-type source, geochemically similar to the plume-type source as a significant end member. However, the possible source of shallow asthenosphere with a MORB-source geochemical signature is less clear. In the Zr/Y vs. Nb/Y diagram (see Fig. 6.7) the Kutch samples lie intermediate between the xenolith end member and OIB end member. In the trace-element distribution patterns and incompatible element ratios for the xenoliths vis-à-vis that of the melanephelinite-basaltes clearly suggest that the SLCM has made a significant contribution to the generation of Kutch magmas. The continental lithospheric mantle, which records histories of melt addition and removal (Carlson and Irving, 1994), and ancient and recent metasomatism (Menzies et al., 1987), is heterogeneous and complexly enriched with EMI and EMII rich reservoirs. In contrast, the plume melt generally will possess HIMU like signatures. Compilation of published Sr-Nd isotopic data on the alkaline rocks from Kutch and their plotting (Fig. 6.6b) clearly reveals the role of Reunion mantle and mixing between HIMU and EMII mantle types but a subdued role of EMI type mantle in the generation of the Kutch alkaline magmas. In addition, the mirroring of the trace element systematics for the spinel-lherzolite xenoliths and their host alkaline rocks (Fig. 6.7b) may imply that either there has been similar metasomatic modification of both the spinel and garnet-lherzolite parts of the mantle or disequilibrium contamination of ascending magmas (the alkaline magma generated in the garnet lherzolite field) as they traveled through spinel lherzolite zone (O’Reilly et al., 1991; Hoang and Uto (2003). Although debated (e.g. Sheth, 2007), the presence of approximately cylindrical region of lower seismic velocities in the upper mantle to the north of the Gulf of Cambay reported by Kennet and Widiantoro (1999) has been interpreted as the initial conduit through which the proposed plume material forced its way through the upper mantle beneath the Cambay rift (Basu et al., 1993, Karmalkar et al., 2005). The presence of such a geophysical anomaly supports the possible involvement of a plume component in the generation of the Kutch alkaline magmatism.
Figure 6.7. Comparisons between the trace element chemistry of the ultramafic xenoliths (diopside) and melanephelinite-basanite rocks from Kutch (after Karmalkar et al., 2005).
6.3 Basalt Magmatism: Unmixing the tholeite cockpit

Spatial and temporal geochemical provinciality characterizes many CFB provinces. The debate regarding the lithospheric vs. asthenospheric origin of CFB melts continues unabated. White and McKenzie (1989), and Arndt and Christensen (1992) have stressed that CFB magmatism should be dominated by melts derived from sub-lithospheric mantle. In contrast, the Mesozoic Gondwana CFB provinces (Parana, Karoo, Ferrar) are dominated by lavas that have trace-element ratios (low Nb/La) and Sr-Nd-and Pb-isotope compositions that are distinct from oceanic basalts and it has been argued that these primarily reflect contributions from incompatible-element-enriched source regions in the sub-continental mantle. As such source regions should be old, some workers have placed them within the continental lithospheric mantle, or at least in part within the mantle that is isolated from vigorous convection (Hawkesworth et al., 1988). Asthenospheric derived melts that have scavenged small-degree lamproite melts from the lithosphere are said to be responsible for the generation of the Gondwana CFB (McKenzie, 1989; Elam and Cox, 1991), while wholesale melting of lithospheric mantle has been envisaged as the major source of Gondwana CFB (Hawkesworth et al., 1988; Gallagher and Hawkesworth, 1992). Arndt and Christensen (1992), on the basis of thermal modeling of lithospheric extension and the impingement of a mantle plume at the base of the lithosphere refuted such possibility and opined that bulk of the CFB originate from asthenosphere. Arndt et al. (1993) proposed that the compositional variations of worldwide CFB provinces reflect differences in the degree of melting of the underlying convecting asthenosphere. According to them, the high-Ti basalts are generated by low-degree partial melting of upwelling mantle beneath thick SCLM and the low-Ti basalts by high-degree melting beneath thinner SCLM. Contrary to this, Gibson et al. (1995) while explaining the genesis of 'high-Ti and low-Ti mafic potassic magmas' from the Parana CFB have invoked contribution of up to 50% of fusible mafic potassic melts. Variable involvement of upper crustal component as the basis for the low-Ti and high-Ti nature of the basalt has also been suggested by others (e.g. Hergt et al., 1991). In the southern Parana of Brazil and the related Etendeka province in Africa, crustal-level contamination has clearly been an important process in the evolution of the low-Ti magmatism (e.g. Mantovani et al., 1983; 1985; Petri et al., 1987; Mantovani and Hawkesworth, 1990).

Five dykes i.e. Chawadka (KCh3), Dhrubiya (KEx), Paiya (KPO1, KPO2), Habai (KH1), one laccolith (KS2, Dhrang), one sill (KRI1, Reidi) and two lava flows (KRhl-
Roha, KBgs2-Kukma) represent the tholeiite samples from the study area. In general, the basalt from the study area have a considerable SiO$_2$ (47.21 to 50.2 wt. %), MgO (3.54 to 8.64 wt. %), Mg$#$ range (44.76 to 65.64) and TiO$_2$ (0.69 to 3.9 wt. %). All the basalt samples are hypersthene normative and confirm their tholeiite character (Verma et al., 2002). Four samples i.e. Chawadka (KCh3), Paiya (KPO1), Habai (KH1), and Reldi (KRI1) are olivine normative. Besides, samples Dhrubiya (KEx), Paiya (KPO2), Dhrang (KS2), Roha (KRh1) and Kukma (KBgs2) are quartz normative. The CaO content in the basalt exhibit positive correlation with Mg$#$. This is in contrast to the alkaline rocks from Kutch, which shows decrease in CaO with increasing Mg$#$. The increasing trend in case of the tholeiites indicates fractionation of plagioclase and clinopyroxene with minor olivine. On the basis of major oxide, and oxide ratios the basalts can be grouped in two distinct geochemical subtypes viz. high-Ti and low-Ti basalts. Both group exhibit typical tholeiitic trend of TiO$_2$ and Fe$_2$O$_3$ enrichment as MgO falls indicating role for magnetite fractionation.

6.3.1. High-Ti Basalt: OIB Lineage

Four samples i.e. Chawadka (KCh3), Dhrubiya (KEx), Reldi (KRI1) and Kukma (KBgs2) show Al$_2$O$_3$/TiO$_2$ ratio < 8. Similarly, the four samples have low CaO/TiO$_2$ (2.51 to 3.64) and are very different from the remaining basaltic samples (8.84 to 19.01), which are similar to 6-17 reported for CaO/TiO$_2$ in MORB and thus belong to the high-Ti group. It is to mention that all basalt samples from the high-Ti group plot in the OIB field. On the contrary in the primitive mantle normalized semi-log plot these samples show striking similarity with the pattern shown for N-MORB. However, the samples show an elevated incompatible element and LREE pattern and many of the trace element oxide ratios are much different from the MORB and shows close OIB affinity. The high-Ti picritic basalts from Kathiawar region of Gujarat are shown to be chemically and isotopically similar to the recent shield lavas of the Reunion hotspot (Melluso et al., 1995, 2006). The origin of high-Ti and their elevated incompatible trace elements have been variously ascribed to one or more of the following processes:

(a) the effects of crustal contamination (Fodor, 1987),

(b) contamination by (subduction-related) sub-continental lithosphere (Duncan, 1987; Murphy, 1988), and
(c) derivation from enriched mantle either of the type that produces enriched MORB or kimberlite mantle.

On the basis of negative Pb anomaly and positive Nb anomaly as well as on the basis of various trace element oxide ratios, the role of crustal contamination is refuted in case of these Kutch samples. According to Arndt et al. (1993) the compositional variations of worldwide CFB provinces reflect differences in the degree of melting of the underlying convecting asthenosphere. High-Ti basalts are generated by low-degree partial melting of upwelling mantle beneath thick SCLM (Arndt et al., 1993). In the Ce/Y vs. Zr/Nb plot (Fig.6.5a) the high-Ti basalts plot along with the melanaphilitite-basaltite samples and constitute a trend that falls well above the spinel facies. From the figure it is clear that the basalts plot slightly below the trend for the garnet facies i.e. in the transition zone between garnet and spinel facies with higher degrees (>2%) of partial melting. Similarly, in the La/Yb vs. Tb/Yb diagram (Fig. 6.5b) the high-Ti basalts rocks plot between 0 to 2% melting curves and suggest that they were generated by melting 1% modal garnet in garnet lherzolite field (Macdonald et al., 2001). The geographic occurrence of the basalts in the areas proximal to the melanaphilitite-basaltite plugs suggests a spatio-temporal relationship between the two. Off the nine flows exposed and studied in the Anjar section (Shukla et al., 2001), the lower 8 flows are shown to be alkaline in character and closely resemble the high TiO$_2$ OIB-type samples from the present study. Therefore, it is speculated that similar sources must have been involved with variable degree of partial melting in the genesis of the melanaphilitite-basaltite and high-Ti basalts. Alternatively, based on the closely comparable Ti/Y and La/Nb ratios of the basalts to the melanaphilitite-basaltite it can be concluded that the high-Ti basalts represent mixing of melts derived from both the convecting asthenospheric mantle (plume?) and the SCLM. The field relation and similar major oxide, trace and REE signatures of the Reldi sill and the Kukma flow indicates that the sill may have fed the flow. This indicates that several dykes and sills tapping distinct high-Ti magma chambers could act as feeders to high-Ti flows in Kutch. A concerted efforts therefore need to initiated in identify such dyke-flow relations in the near future.

6.3.2 Low-Ti Basalt: Messengers of upwelling asthenospheric mantle.

The five samples i.e. Paiya (KPO1, KPO2), Habai (KH1), Dhrang (KS2), Roha (KRhl) represent the low-Ti basalts group from the present study. These have Al$_2$O$_3$/TiO$_2$ ratio between 11.66 and 20.87 and are similar to the MORB (8 to 20) ratio of Sun et al.
(1979). The geochemistry of the basalt samples from this group can be best described as that belonging to MORB. Similarly, in the Zr/Hf versus Nb/Ta diagram all the samples plot in the field for continental basalts, but the 5 samples of the low-Ti basalt group typically indicate MORB like characters. Melluso et al. (2006) have similarly shown that many of the trace elemental characters of the low-Ti picritic basalts from the Kathiawar region of Gujarat are similar to those of transitional or normal ocean ridge basalts. The average continental crust shows a positive Pb anomaly and negative anomalies for Nb, P and Ti (Taylor and McLennan, 1985). The Kutch samples, excepting Dhrubiya essexite sill (KEx) and Roha flow (KRh1), do not show negative Nb anomaly. On the contrary, all of them including KEx and KRh1 exhibit strong negative Pb anomaly refuting the role of crustal contamination in the genesis of these rocks. However, in the samples KEx and KRh1 the Rb/Sr ratios (0.11 and 0.1) are closer to the ratios for continental crust (Rb/Sr: 0.12). The higher Ba/Nb (13.83 and 18.41) and Ce/Pb (15.0 and 10.87) in these samples when compared to the rest indicates feeble contribution from the continental crust (Rb/Sr: 0.12, Ba/Nb: 22.73, Ce/Pb: 4.13) in the genesis of these rocks. The genesis of the low-Ti picritic basalts from Kathiawar region Gujarat has been attributed to a) crustal contamination of ascending magmas, b) a minor component within the Indian lithospheric mantle of anciently subducted sedimentary material, or c) fluids derived from subducted material (Melluso et al., 2006). Hawkesworth (as quoted by Peate and Hawkesworth, 1996) demonstrated that even within a localized area, the contamination process is complex and can not be represented by a single, progressively contaminated liquid line of descent. Peng et al. (1994) have proposed a complex two-stage contamination model for the compositions of the lower formations from the Deccan CFB, which emanate from a “common signature” composition and form arrays attributed to secondary contamination episodes involving several crustal end-members. Peate and Hawkesworth (1996) while studying the low-Ti basalts from CFB in the southern Parana, Brazil, opined that the compositional shift simply can not be attributed to declining extent of crustal contamination of asthenosphere derived melts with time, but require two magma types evolved from two distinct parental magmas. Although several workers favour a major role of crustal contamination in the evolution of low-Ti magmas, the principal disagreement has been over the composition of the “uncontaminated” parental magma(s). As already stated, out of the limited number of samples analysed a few exhibit limited or feeble crustal contamination. Thus, in the present case it appears that crustal contamination alone can not explain the generation of the low-Ti
character of these basalts, but goes to indicate existence of a separate parental magma in their evolution. In the Ce/Y vs. Zr/Nb plot (Fig. 6.5a) the low-Ti basalts samples plot well below the garnet facies and follow the trend for the spinel facies with 1.5 to 2.5% degree of partial melting. This is corroborated by the fact that very little garnet is involved in their genesis (Fig. 6.5b). While explaining the genesis of the Kilauea tholeiites from Hawaii, it is argued that the observed trace element variation of these is consistent with low degree partial melting of garnet lherzolite (Hofmann et al., 1984; Budahn and Schmitt, 1985). On the contrary, experimental studies have shown that the primary or primitive tholeiites are not in equilibrium with garnet lherzolites, but are in equilibrium with more refractory harzburgite at lithospheric depths beneath Kilauea (Green and Ringwood, 1967; Egginis, 1992). This is consistent with the higher normative silica content of the tholeiite magmas than experimentally produced melts of garnet lherzolites. Wagner and Grove (1998) on the basis of experimental work have invoked a two stage model for the formation of primary tholeiites. In the first stage, the magmas are generated by the melting of garnet lherzolite in a convecting asthenospheric mantle. In the second stage, the ascent and decompression of magma causes them to react with harzburgite in the mantle by assimilating orthopyroxene and crystallizing olivine. The melt/harzburgite reaction occurs over a range of depth at a mean depth of 42 km (Wagner and Grove, 1998).

From the limited number of sample analysed in the present study it appears that the low-Ti magmatism is more commonly seen restricted to the eastern part of the study area specifically to the Habo dome. It is of interest to note that most of these samples are of dykes that are confined to the east of the study area. Their proximity to the flow (F9) exposed in the Anjar section having similar low-Ti content (Shukla et al., 2001) imply coeval nature of the dyke and flows. Alternatively, some of these dykes could possibly be feeders to the tholeiite flows exposed near Anjar. Based on our limited data set of basalt samples and those published in literature, it appears that there exists a distinct provinciality in the occurrence of low- and high-Ti basalts in the Kutch, which can be attributed to different source regions and degrees of partial melting.

The spatial distribution of magma types in the Kutch region reflects sub-crustal distribution of distinct lithospheric source regions. The high-Ti basalts from Kutch are chemically similar to those reported from shield lavas of the Reunion hotspot and show an OIB type signature. In contrast, the low-Ti basalts are similar to MORB. These findings from Kutch are similar to the high- and low-Ti basalts from NW-India (Melluso et al.,
The incompatible element characteristics of the asthenospheric component contributing to the Kutch tholeiite magmas might be reconcilable with material from the convecting mantle (plume?). Convecting mantle (plume?) when initially impinges at the base of thick lithosphere is prevented from further ascent to shallower depths and limits the degree of melting (Ellam, 1992). Thus melting occurs at high pressures in the presence of garnet, leading to incompatible-element enriched OIB magmas with high Ti/Y with some contribution from lithospheric mantle. If the convecting mantle rises to shallow(er) depths, as a result of extensive lithospheric thinning due to rifting, or thermal erosion, the degree of melting would be higher, producing melts with lower concentrations of incompatible elements and without a residual garnet signature (i.e. MORB-like Ti/Y). The observed compositional shift from lithosphere to asthenosphere dominated chemical signatures with time is analogous to the Garmado and Esmeralda sequence of southern Paraná (Peate and Hawkesworth, 1996) and Siberia (Lightfoot et al., 1993). Many of the Deccan primary magmas could have been derived from mixtures of high-Ti-type, Reunion-like source component and a component more similar to, or even more incompatible-element-depleted than, average ocean-ridge mantle (Melluso et al., 2006). Further detailed investigations are therefore warranted.

6.4. Nature of the lithosphere below Kutch

The composition of the deeper parts of the Indian continental lithosphere is poorly known, although this parameter is essential to model crust-mantle evolution in this part of the world. Mahadevan (1994) has made a significant effort in reviewing the work done on the deep continental crust of India. Mahadevan (1994) indicated the great potential the xenoliths have in constraining the composition and structure of the continental lithosphere. Bezant (1985) carried out ultrasonic velocity measurements on four mantle-derived xenoliths from Australia in the laboratory and found that Vp values calculated using density, M (mean atomic weight), and CaO concentration are higher than those obtained by ultrasonic measurement and applied an empirical correction to the calculated Vp determinations of O’Reilly and Griffin (1985). Vp values were obtained by Bezant (1985) using single-crystal data and the mode of the rock corresponds to within 2 % for the four rocks (O’Reilly et al., 1990). Grids were constructed on this basis for the common mantle rock types so that Vp can be determined graphically from the mode in cases where the assemblage was dominantly three-phase. Considering the similarly between the modal
mineralogy and geochemistry of the xenoliths from Australia and Kutch, the modal data for the Kutch xenoliths were similarly plotted and yielded $V_p$ of 8.1 to 8.2 km/sec, which closely corresponds to the value suggested for the mantle immediately below the Moho discontinuity.

In the Kutch region, Raval and Veeraswamy (1996) using constraints from seismic lines to the south and east have modeled the gravity data. Their model indicates a crust-mantle boundary lying at 35-40 km, and a zone of anomalously light mantle (density ≈ 3.1 g/cc) making up a thickness of ca 10 km below the boundary. This is in turn underlain by material with a density of 3.2 g/cc, extending for another 8-10 km. The model suggests a gradational increase of density with depth below the crust-mantle boundary (CMB), as is observed in many volcanic areas such as eastern Australia (O’Reilly and Griffin, 1985). Rifting and/or mantle plume activity may give rise to a large scale underplating of mafic and ultramafic material in the deep crust (Griffin et al., 1984, Fyfe, 1993; Stein and Hoffman, 1994), which will be reflected in the Bouguer gravity signatures of such regions. Incidentally, in the Sayala Devi plug two kinds of xenoliths have been recovered, one with mantle mineralogy with C-diopside as the main clinopyroxene phase, while the other dominated by augite clinopyroxene and typically showing cumulate textures. The cumulate rock types consisting of the assemblage clinopyroxene ± orthopyroxene ± olivine ± spinel are found in close association with spinel peridotite xenoliths of mantle origin. Such ultramafic xenolith suite were considered by Wilkinson (1975) to represent fractionates of tholeiitic magma within the crust, related to igneous intrusions near the crust/mantle boundary and especially in the uppermost mantle. Griffin and O’Reilly (1987) similarly interpret the mafic layers to have been formed by repetitive intrusion and ponding of basaltic melts near the crust mantle boundary due to density contrast between crustal rocks and mafic magmas. Similarly, the low-Ti basalts have been significantly underplated as sills, lacoliths and dykes within the string of domes straddling the Kutch Mainland Fault. This underplating process may have contributed substantially to crustal growth in the Kutch region and the mafic rocks may have significantly influenced the bulk density of the uppermost mantle.

Low equilibration temperatures (884-972°C) calculated for the Kutch xenoliths indicate entrainment of harzburgite and lherzolite xenoliths from shallow depths within the lithosphere (Karmalkar et al., 2000). Since the Kutch xenolith suite is devoid of crustal
granulites and garnet bearing xenoliths, it is impossible to construct an independent geotherm for the region. Hence, xenolith data from Kutch was plotted in the established southeastern Australian geotherm and West Coast geotherm (Murad-Janjira) of India (Fig. 6.8). The estimates of pressure derived from the southeastern Australian geotherm (SEA) for the Kutch xenoliths are shallower than the estimated depth of the crust mantle boundary (35 to 40 km) beneath Kutch, derived on the basis of gravity data by Raval and Veeraswamy (1996). The granulite xenoliths from the West Coast lamprophyres (Dessai et al., 1999) have yielded a temperature range of 500-900°C and pressures of 6-11 kbar corresponding to a depth of 20-35 km. Dessai et al. (1999) have therefore assigned a lower crustal origin to these xenoliths, in concurrence with the, reports of similar xenoliths, from other parts of the world (O’Reilly and Griffin, 1985, 1987, 1995; Griffin and O’Reilly, 1987; O’Reilly et al., 1989a,b; Rudnick et al., 1992; 1994). This elevated West Coast geotherm (Dessai et al., 1999; Dessai and Vaselli, 1999) implies that this region is characterized by abnormally high heat flow, which is also evident from a linear array of 24 hot springs along the West Coast. Correlating this thermal profile with the existing seismic data, a crust-mantle boundary that is transitional, over depth range of 15-25 km has been envisaged for the area.

The depth to the CMB in Kutch extrapolated from the West Coast geotherm of Dessai et al. (1999) is slightly deeper i.e. 45 to 50 km (Fig.6.8, 6.9). If the geophysically based estimate is taken as minimum depth for the occurrence of ultramafic rocks (spinel bearing harzburgite and lherzolites) then the geotherm beneath Kutch at the time of eruption was slightly less elevated than those for southeastern Australia and the western continental margin of India (Karmalkar et al., 2007). In either case the temperatures suggest that the xenoliths studied resided in the uppermost part of the mantle at the time of entrainment in the melaneplinite-basanite magmas, and that many have cooled from significantly higher temperatures before they finally were entrained. Several samples retain evidence of an early high-T history, recorded by high Al and/or Ca in the cores of pyroxene grains; these give temperatures as high as 1360°C with the Sachtleben and Seck (1981) and Witt-Eickenschen and Seck (1987) geothermometers. The crust/mantle boundary at a depth of 40 km, as derived from the xenolith data, is in close correspondence to the magnetic interface at a depth of 40 km (Agarwal et al., 1992) deduced from the 2-D Magsat vertical intensity map of Arur et al., (1986). These estimates also tally well with the Curie depth calculated by
Figure 6.8. Geotherm of the western continental margin of India (after Dessai et al., 2003) using the xenolith data of Murud and Kutch. Also shown is the geotherm of South East Australia (SEA) after the Bullenmerri/Gnotuk xenolith data (O’Reilly and Griffin, 1985).
Figure 6.9. Schematic section across central Kutch depicting the lithosphere-asthenosphere boundary and the origin of different types of magmatism. The lamproite magmatism is shown to be derived from at or above the lithosphere-asthenosphere boundary from metasomatized garnet harzburgite or metasomatized cratonised keel.
Negi et al. (1987) based on the heat flow data and the depth to Moho for the area estimated by both gravity and DSS data (Kaila et al., 1981; Raval and Veeraswami, 1996).

Xenoliths derived from upper and lower crustal levels viz. felsic and mafic granulites are absent in the Kutch region and there is a preponderance of spinel peridotite xenoliths of mantle origin. Examples of upper crustal fragments are known from the basaltic dyke rock exposed at Mandaleshwar in the Narmada River that lies few hundred kilometers to the SE of the Kutch region (Duraiswami and Karmalkar, 1996). The basaltic dyke 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 Cretaceous 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 underlying the thick crustal ‘basaltic’ layer. Similarly, diverse crustal xenoliths are reported from the Rajmang and Talwade dykes near Dhule, proximal to the Tapti graben (Ray et al., In Press). However, the absence of crustal xenoliths in the alkaline magmatism from Kutch implies that either the magmatism did not penetrate a granitic basement or no granitic basement exists beneath Kutch. The lower crustal contamination in the alkaline and tholeiite magmatism corroborates well with the limited interaction with a granitic basement. The absence of granitic basement beneath Kutch can be explained by invoking a rift environment wherein the granitic basement is replaced by a relatively juvenile basaltic crust.

The spinel harzburgite and lherzolite xenoliths from Kutch are derived from a depth range of 45-50 km. In comparison, at Murud-Janjira, the pyroxenites and not the spinel lherzolites are the potential rocks at this depth. It is therefore quite likely that the crust mantle transition is more diffuse beneath Murud-Janjira than beneath Kutch. However, the presence of hydrous phases such as phlogopite, kaersutite and apatite in the pyroxenites and wehrlites are indicative of modal metasomatism, which indicates that the mantle at Murud-Janjira is metasomatically veined. At a depth of 45-50 km, the mantle rocks below Kutch have also undergone metasomatism, but the style of metasomatism is different, i.e. cryptic metasomatism (Karmalkar and Rege 2002).
The paucity of pyroxenites and wehrlites in the Kutch region are suggestive of low fluid to rock ratio. The pyroxenites and granulites exhibiting igneous textures are interpreted as igneous cumulates and represent frozen basaltic melts that characterize the portion above and below the crust-mantle boundary (Griffin and O’Reilly, 1987). Zones with abundant horizontal reflectors are observed at depths of 15-35 km in many parts of the continental crust (Meissner et al., 1983; Kaila, 1989). These zones are in many cases described as continental crust and the seismically transparent zone below this as the mantle. Griffin and O’Reilly (1987) argued that such studies do not constitute evidence that either the Moho or the base of the layered zone corresponds to the crust-mantle boundary. Because of the intermixing of mafic rocks as sub horizontal lenses within the mantle material such zones will have a bulk density and Vp intermediate between “crust” and “mantle” values. To reconcile the petrological and seismic data in such areas Griffin and O’Reilly (1987) place the crust-mantle boundary in the middle of the layered zone. In the Kutch area, the Moho is shallower and sharply defined as is evident from the presence of spinel-lherzolite xenoliths and absence of granulite or pyroxenites xenoliths. However, mafic-ultramafic xenoliths of cumulate origin are abundant especially in the Sayala Devi plug. The point that needs to be addressed is the absence of mafic granulite and eclogite xenoliths from the Kutch region. The main difference perhaps lies in the physical environment between the Kutch and Murud-Janjira regions i.e. the slightly lower geothermal gradient in the former. Temperature is believed to be the critical parameter determining whether mafic rocks are in granulite or eclogite facies, which in turn will govern the Vp. Magmatic underplating will be accompanied by an elevated geotherm similar to the one at Murud-Janjira. On such elevated geotherm a greater range of mafic compositions will enter the granulite field at relatively greater depth. When the magmatic activity ceases, this geotherm will decay towards a conductive geotherm, and during such cooling mafic rocks will enter the eclogite field at relatively shallow depth and mafic granulite may transform into eclogites, if kinetic factors are favourable. The transition from garnet granulite to eclogite results in an increase in Vp of 0.5-1.0 km/sec (O’Reilly and Griffin, 1985), and the decrease in temperature will further raise the Vp of the mafic rocks. The overall effect of such changes would be an increase in Vp that is greatest at CMB where the concentration of mafic rocks is highest. Geophysically, the Moho in such regions will move upward and become more pronounced as a result of cooling (O’Reilly and Griffin, 1985).
The elevated geotherm at Murud-Janjira (West Coast) may be due to heating probably due to mantle swelling or upwelling and intrusion of magmas (dyke swarms) into the upper mantle and lower crust (Hooper, 1990). Thinning of the lithosphere while undergoing extension may cause such a thermal perturbation. The absence of both mafic granulite as well as eclogite xenoliths and presence of ultramafic cumulates from Kutch region perhaps may be attributed to early cessation of magmatic activity and rapid cooling, which did not allow sufficient time for equilibration to lower-T mineral assemblages. This is consistent with the small-scale nature of the alkaline igneous activity and subsequent limited volcanism in this part of the DVP, in contrast to the large-scale flood-basalt magmatism in the DVP mainland. Limited extraction of melt in upwelling mantle (plume?) in this region could leave sufficient temperature excess further south towards the Murud-Janjira region. This inference could further support the fact that the Kutch region passed over the proposed plume head much earlier than the Murud-Janjira region, which is consistent with the rapid northwestward movement of the Indian plate (140-200 mm/yr) after its separation from Gondwanaland (Kent et al., 1992).

It is speculated that the Indian plate has also interacted with other mantle plumes on at least two previous occasions i.e. at ~117 Ma (Kerguelen plume-Rajmahal-Kerguelen Plateau basalts) and again at ~84 Ma (Marion plume- Madagascar tholeites). Thus, in the regional context, western India probably had a thin mechanical boundary layer beneath it at the time of its interaction with the Reunion plume. An asthenospheric depth of 70 km and a Moho at a depth of 30 km is tentatively inferred from geoelectrical model below Valsad (Singh et al., 1989). A temperature of 900°C for the Kutch xenoliths at 30 km depth intersects an equilibrium surface heat flow of about 90 mW/m². However, a model 90 mW/m² geotherm intersects the dry peridotite solids at a depth of about 80 km. From these simple considerations, it is inferred that the lithospheric thickness below the Kutch region may not have exceeded 80 km at the time of Deccan volcanism (Mukherjee and Biswas, 1988). The alkaline rocks in Kutch entrain only the spinel peridotite xenoliths and not the garnet peridotite perhaps indicating that alkaline rocks here have not reached the entire thickness of the SCLM that existed at the time of Deccan volcanism. However, the chemistry of the host melanephelinite-basanite-alkali basalts clearly suggests derivation from deeper depths i.e. 80-100 km in the granit herzolite field (Fig. 6.9). As already stated, numerous workers consider lamproites as small volume partial melts of a subcontinental lithospheric mantle source that was enriched by metasomatism prior to melting.
and derived from a deeper depth of 100-150 km (Fraser et al., 1985; Mitchell and Bergman, 1991; Edgar and Mitchell, 1997; Rao et al., 2004). The reported occurrence of lamproite in the Kutch region proximal to the Kutch Mainland Fault implies lithospheric thickness of ~ 100-110 km (Fig. 6.9). It is suggested that giving local allowances to the minor perturbations, the overall thickness and the lithological composition of the lower crust and the nature of the crust-mantle transition may be similar all along the western continental margin of India. The large differences in seismic signatures can be interpreted as due to the differences in thermal regime as well as the metasomatic history of the region similar to the eastern and western continental margin of Australia. Thus in the future, the gravity as well as the seismic data should therefore be interpreted keeping these features in mind.