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Petrology, geochemistry and paleomagnetism of the earliest magmatic rocks of Deccan Volcanic Province, Kutch, Northwest India

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Abstract

Tholeiites and alkali basalts occurring in the southern coastal belt of Kutch rift basin, Gujarat are the northernmost on-land exposure of Deccan Traps. Further north, mafic dykes, sill and a differentiated alkaline plutonic complex occur along deep-seated rift-related faults. The major rift-related faults provided the channel ways for the emplacement of the magmas to the surface. These magmatic rocks have been classified into three Groups on the basis of spatial distribution, mode of occurrence and petrochemistry. Petrological, geochemical and paleomagnetic data for the representative samples of the volcanic and intrusive rocks from Kutch region are presented. The alkali basalts are enriched in LILE and LREE compared to the Deccan tholeiitic basalts. Paleomagnetic investigations of thirty magmatic bodies of Kutch yield a Virtual Geomagnetic Pole (VGP) at 33.7°N and 81.2°W (dp/dm = 5.81/9.18). This obtained pole is statistically concordant with that of the Deccan Super Pole (36.9°N:78.7°W). The magmatic rocks of the Kutch basin are broadly contemporaneous straddling 30N–29R–29N chrons. It is suggested that the magmatic rocks of Kutch were generated by the impact of the Réunion plume on the Kutch lithosphere under extensional setting.

Keywords: Deccan Volcanic Province; Paleomagnetism; Petrogenesis; Plume; Rift

1. Introduction

The Deccan Traps cover an area of about 500,000 sq. km in Western India (Fig. 1). Considerable thickness of Deccan Trap flows also extends over the continental shelf almost up to the 68° E longitude. To the north, the flows extend up to the southern part of Kutch District of Gujarat across the Gulf of Kutch. The magmatic rocks of Kutch mark the northern limit of the Deccan Trap volcanic activities that took place during Late Cretaceous–Early Paleocene period across the K–T boundary (Shukla et al., 2001), when the Indian plate passed over the Réunion hot spot. Some of the oldest flows of the Deccan volcanic activity are exposed along the coastal belt of the Gulf of Kutch. Further north, the Deccan Traps thin out against the Mesozoic rocks and were eroded away barring a few outliers. The erosion of the Trap cover exposed several feeder plugs and other intrusives and a few volcanic vents. Besides, the petrochemical comparison of the Deccan Traps of northwestern India (including Kutch region) and the well-studied sections of the Western Ghats make the rocks of Kutch particularly interesting to study.

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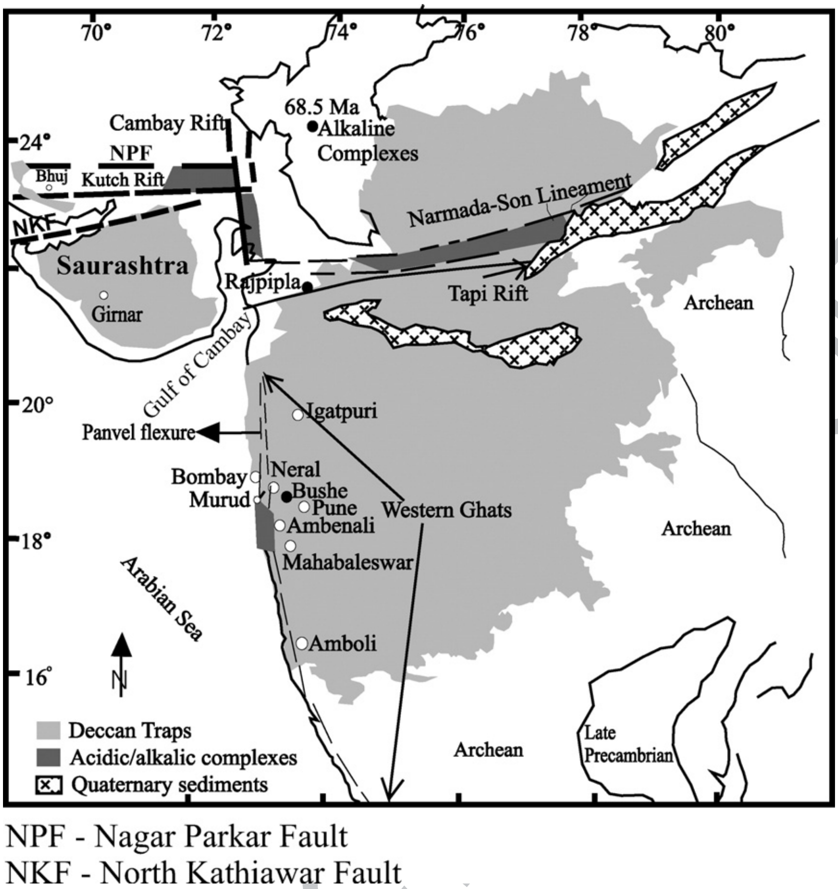


Fig. 1. Map of western India showing the location of the Deccan Volcanic Province (DVP) (light shaded area), the Son-Narmada lineament, the Cambay and Kutch rifts. Distribution of alkaline complexes in the DVP is also shown (dark shaded area). Location of Bhuj, area of the present study, is in the ~~western~~ corner.

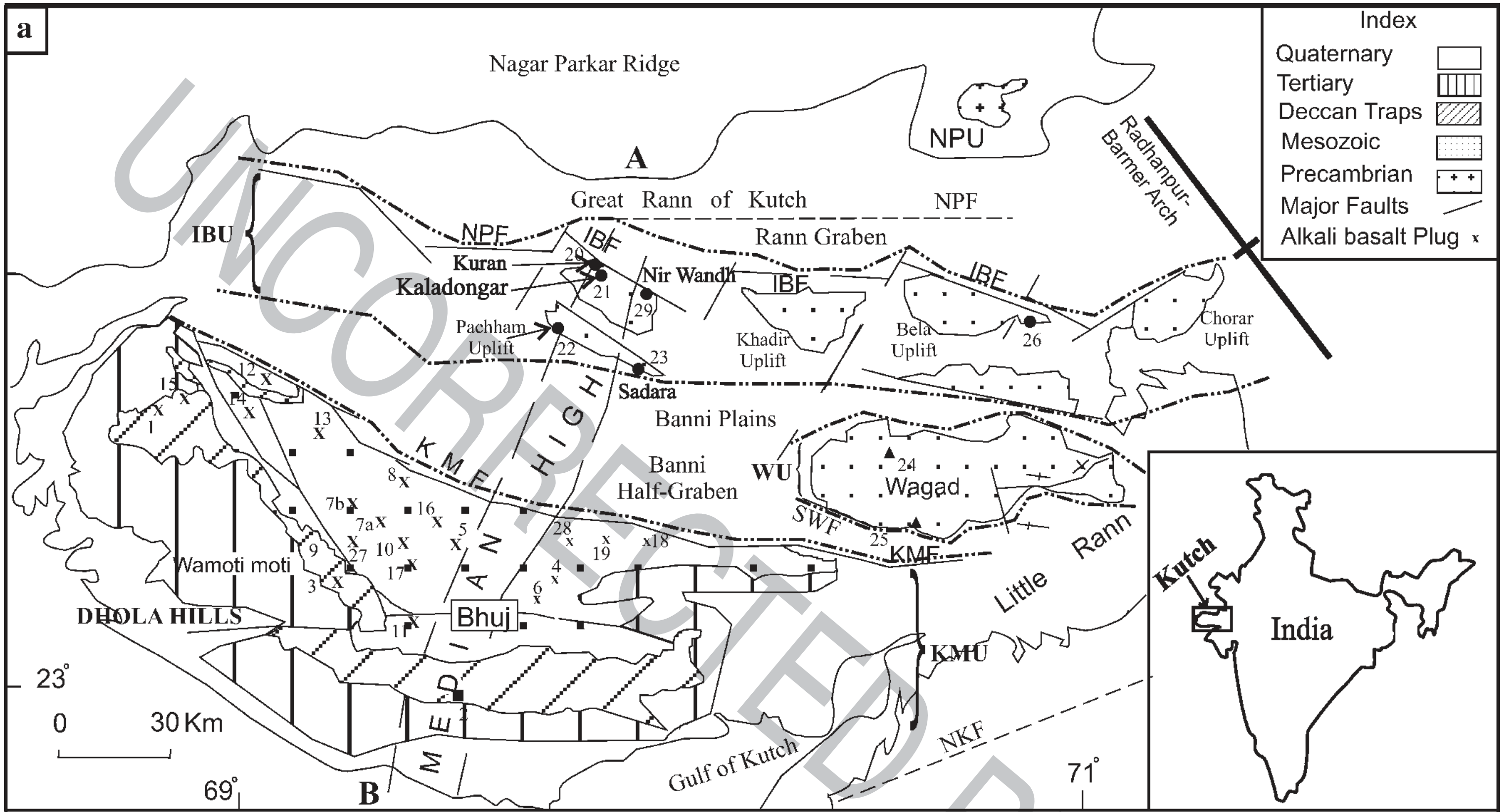
1.1. Geological setting

1.1.1. Tectonic framework and structure

The Kutch Basin located at the western margin of the Indian craton, is an east-west oriented pericratonic rift-basin (Biswas, 2002). The Nagar Parkar Fault (NPF) bounds the rift on the north and the North Kathiawar Fault (NKF) limits it to the south (Fig. 2a). The rift basin is featured by intra-basin tilted fault blocks and intervening half-grabens (Fig. 2b). The uplifts stand out conspicuously as highlands amidst the extensive mud and salt flat over the intervening structural lows-Rann Graben (RG), Banni Half-Graben (BHG) and Gulf of Kutch Half-Graben (GOK). Rocks are exposed in the highlands whereas the flatlands are covered by Holocene sediments. Three uplifts occur along parallel strike faults forming ridges of varying dimensions. These east-west trending uplifts are (Fig. 2a): the Island Belt Uplift (IBU) to the north, the Kutch Mainland Uplift (KMU) in the south with the Wagad Uplift (WU) in the central part. The "Island Belt" is a metaphorical name given to an E–W chain of highlands standing like "islands" on the vast expanse of the mud and salt flat. The Island Belt Uplift along the E–W master fault consists of four smaller uplifts separated by NE–SW wrench faults, viz., Pachham Uplift (PU), Khadir Uplift (KU), Bela Uplift (BU) and Chorar Uplift (CU) (Fig. 2a) forming a chain of "islands". The highland representing the largest uplift and the southern segment of the rift basin adjacent to the Gulf of Kutch is known as the "Kutch Mainland".

A first order meridional basement high called Median High (MH) extends across the uplifts and the half-grabens (Fig. 2a). This High divides the Kutch Mainland Uplift symmetrically and the Pachham Uplift is situated on it. On the east, the rift basin terminates against the NW–SE trending Radhanpur–Barmer basement Arch that separates this E–W rift and the NW–SE Cambay rift (Fig. 1).

The rifting of the Kutch basin started during the early phase of India–Africa separation in Late Triassic–Early



Index to localities:
1. Pranpur, 2. Dhanoi, 3. Wamoti Moti, 4. Bhujia, 5. Bharar, 6. Kingriya Dongar, 7a. Vithon, 7b. Nakhatrana, 8. Dinodhar, 9. Ranadada, 10. Jaksh, 11. Dhrubia, 12. Kaya Dongar, 13. Keera Dongar, 14. Lakhpa-Khatieu, 15. Likhi Hill, 16. Dhar Dongar, 17. Nana Dongar, 18. Jawharnagar-Kanyaber, 19. Lodai, 20. Kuran, 21. Kaladongar, 22. RaimAlro, 23. Sadara, 24. Tromau, 25. Chitrod, 26. Sutana Dongar, 27. Sayra Dongar, 28. Habo Dome, 29. Nir Wandh Complex.

NPU - Nagar Parkar Uplift; NPF - Nagar Parkar Fault; IBF - Island Belt Fault; IBU - Island Belt Uplift; KMF - Kutch Mainland Fault; KMU - Kutch Mainland Uplift; WU - Wagad Uplift; NKF - North Kathiawar Fault; SWF - South Wagad Fault.

Fig. 2. a: Generalised geological map of Kutch (after Biswas, 2002) showing sampling sites for the present study. For abbreviations see text under Geologic setting-tectonic framework. b: Geological section along AB in Fig. 2a. The intrusives in the northern Island Belt Uplift occur along the deep faults shown in the section.

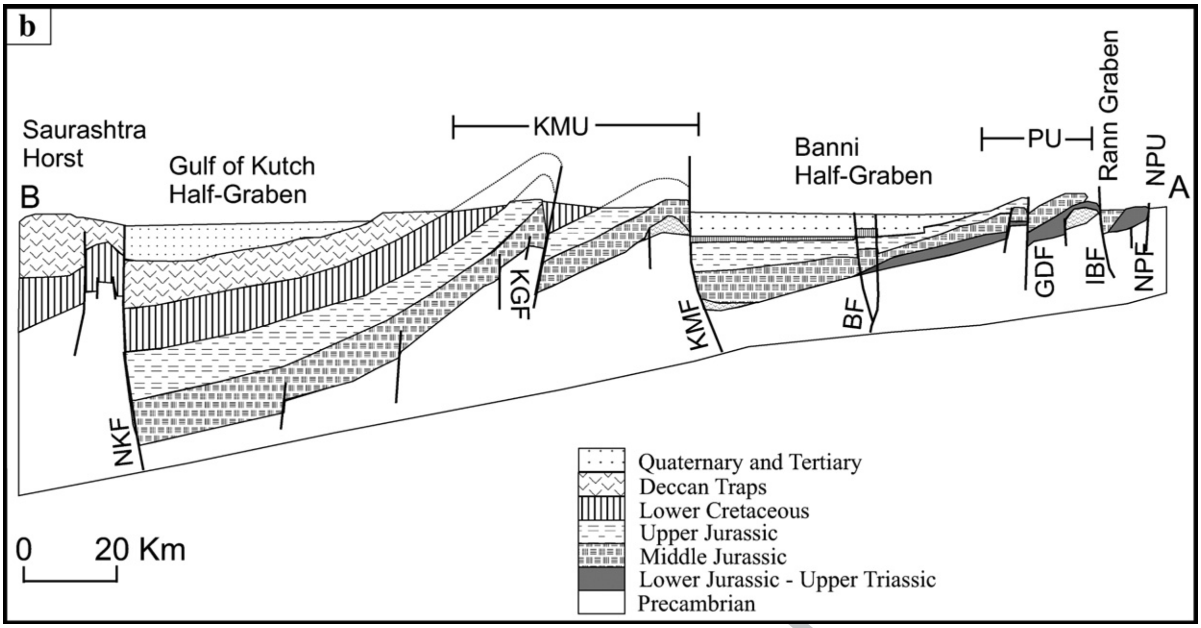


Fig. 2 (*continued*).

Jurassic and ended with the rift-drift transition of the Indian plate in Early Cretaceous as the Seychelles–Mascarene Plateau finally rifted away from Western India (Biswas, 1987).

1.1.2. Magmatic activity

The Mesozoic rocks of the Kutch Basin were affected by intense magmatic activities that left signatures in the form of dykes, sills, plugs, laccoliths and ring dykes. These magmatic rocks can be classified into three groups, on considerations of spatial distribution and mode of occurrence in relation to tectonic setting: tholeiitic basalt, dolerite and gabbroic dykes of Kutch Mainland; alkali basalt plugs of Kutch Mainland; and the alkaline intrusives including lamprophyres of Kutch Island Belt. The eruptive activity is represented by alkali basalt and tholeiitic basalt flows (Guha et al., 2005). Magmatic rocks are fairly common in all the uplift areas. Gravity-magnetic data indicate the presence of igneous intrusives beneath the recent sediment cover in the structural lows (Biswas, 1980). They are mainly concentrated in the narrow deformation zones accompanying the master faults of the uplifts. The maximum density of magmatic activity is present in the northwestern part of Kutch Mainland Uplift, west of the Median High and in the northern part of Pachham Uplift. The occurrence of dykes and other intrusives along faults and in the marginal deformation zones of the uplifts indicate the control of the pre-existing tectonic elements of the basin in the emplacement of the magmatic rocks. A number of alkali basalt plugs occur along a belt in the central region of Kutch Mainland and several alkaline intrusives occur in the northern part of Pachham Island (Fig. 2a). In other uplifts in eastern Kutch, only dykes and sills are present. In the dominantly tholeiitic Deccan Volcanic Province, alkaline rocks are volumetrically small (Bose, 1980). Alkaline rocks are, however, known in the neighboring areas of Gujarat and Maharashtra from Mount Girnar Igneous Complex (Bose, 1973; Paul et al., 1977), Amba Dongar Carbonatite Complex (Chatterjee et al., 1992), Rajpipla (Mahoney, 1988) and around Murud, south of Mumbai (Dessai et al., 1990) (Fig. 1). Of all these, only the alkaline basalts of Kutch contain ultramafic (mostly wehrlite) xenoliths.

Tholeiitic basalt flows are exposed only in the southern part of Kutch Mainland in a 10 km wide belt forming the Dhola Hills (Fig. 2a). The Deccan Traps continue beneath the Tertiary sediments towards south in the Gulf of Kutch and across the North Kathiawar Fault (Fig. 2a). It is exposed again in Saurashtra plateau (Biswas and Deshpande, 1973). In the adjacent Cambay rift and further south in the western offshore basin, the Deccan Traps form the basement of Tertiary sediments. Thus, the tholeiitic basalts of Kutch are continuous with the Deccan Volcanic Province of western India. The progressive northward thinning of the Deccan Traps from 1500 m in the Deccan Volcanic Province type area in Maharashtra to 100 m in Kutch and breaking up of outcrops into detached outliers farther north suggests that the Kutch and North

Gujarat outcrops are the northernmost occurrences of the Deccan Traps. The Kutch Mainland Fault marks the northern limit of the volcanic field. This is corroborated by the absence of tholeiitic basalt flows further north beyond the Kutch Mainland Fault and in the intervening structural lows as indicated by the geophysical as well as deep drilling data (source-Oil & Natural Gas Corporation Ltd., India). The tholeiitic basalt flows disconformably overlie the Mesozoic rocks.

In this paper, we present petrological, geochemical and paleomagnetic data on the magmatic rocks of Kutch with a view to explore the relationships among the three groups of magmatic rocks mentioned earlier. Particularly, we want to study the magmatic manifestation of the impact of a mantle plume on the lithosphere beneath the Kutch rift zone and the nature of the subcrustal lithosphere of the region. As the tholeiitic basalts of Kutch are believed to be the oldest flows of the Deccan Volcanic Province (Basu et al., 1993), this area provides an excellent opportunity to study the onset of Deccan volcanism.

2. Petrology and mineralogy

As stated earlier, the magmatic rocks of Kutch basin include both extrusive and intrusive components. The extrusive components are represented by thick flows of tholeiites occurring along the coastal belt of Kutch Mainland Uplift (KMU). Six flows have been traced in the field with a very gentle 5° southerly dip. In close spatial association with the tholeiitic basalts, dolerite and gabbroic intrusives are common in KMU. The intrusive rocks occur in the form of dyke swarm, laccolith and plutons. They are mineralogically similar to the tholeiitic basalts (Table 1). These two categories of magmatic rocks, i.e. the Kutch Mainland tholeiitic basalts, dolerite and gabbro constitute Group-I for the purpose of this paper. A characteristic feature is the occurrence of a large number of alkali basalt plugs in KMU along a linear WNW–ESE belt (Fig. 2a). Most of these plugs are intrusive into the Cretaceous Bhuj Formation and contain mantle derived ultramafic xenoliths (De, 1964; Mukherjee and Biswas, 1988; Krishnamurthy et al., 1989). Some of these alkali basalt plugs are associated with pyroclastics as in Vithon and Dhrubia (Fig. 2a). The ultramafic xenoliths are very small in size (3 cm), mostly platy in character. Compositionally, a majority of the xenoliths are wehrlite with subordinate lherzolite and dunite. These xenolith bearing alkali basalts are not found elsewhere in the Deccan Volcanic Province. The alkali basalts from KMU constitute Group-II magmatic rocks.

In the northern Island Belt Uplift, intrusive rocks occur in the form of dykes, sills and plutons particularly in the Pachham area. Of these, melagabbroic rocks occur around Kuran, mafic dykes at the core of the Kaladongar anticline, mafic sill around Sadara (Ray et al., 2006) and a differentiated plutonic igneous complex around Nir Wandh (Fig. 3). The main rock types in the Nir Wandh include pyroxenite, alkali gabbro, alkali diorite, nepheline syenite and lamprophyre. All these intrusives occur in the zone of intense deformation characterised by faulting and folding (see N–S geological section in Fig. 2b). These intrusive rocks of Pachham Island have been classified under Group-III.

The volcanic rocks of Kutch basin are classified using TAS diagram and the plutonic rocks are classified on the basis of modal mineralogy using QAPF diagram and pyroxene–plagioclase-hornblende diagram of IUGS (Le Bas and Streckeisen, 1991). Petrographic descriptions of these magmatic rocks are given in Table 1.

3. Geochemistry

Major element analyses were carried out using X-ray fluorescence technique with a Philips MagiX-PRO PW2440 fully automatic, microprocessor controlled X-ray spectrometer equipped with a 4 KW X-ray generator. International rock standards from the US Geological Survey and Geological Survey of Japan were used to prepare calibration curves. Total iron was measured as Fe_2O_3, which was converted to FeO and divided between FeO and Fe_2O_3. 85% of the total iron was allotted as FeO and the remaining 15% as Fe_2O_3. The trace elements were determined using a Perkin Elmer SCIEX, Model 6100 ELAN DRC II ICP-Mass Spectrometer with a Meinhard nebulizer for sample introduction. The detailed analytical procedure is given by Balaram and Gnaneshwar Rao (2003). The major and trace element analyses were carried out at the National Geophysical Research Institute laboratories, Hyderabad. The major and trace element composition of International Standard, JB-2, were determined, in duplicate, during the present analysis and the results are given in Table 2. The results indicate the accuracy and precision of the present analytical data.

Major and trace element abundances of representative samples of the magmatic rocks from both the Kutch Mainland and the Island Belt are presented in Table 2. The analytical results on the individual samples are available with the supplementary database of the Journal. The relevant data are plotted in total alkali–silica (TAS) diagram (Le Bas and Streckeisen, 1991) (Fig. 4). In this diagram, the Kuran gabbro samples of the Island Belt plot in the picro-basalt field. The Sadara

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t1.1 Table 1

t1.2 Petrographic description of magmatic rocks of Kutch basin

t1.3	Group	Rock type (locality)	Petrographic description	Classification after IUGS (Le Bas and Streckisen, ~~1992~~) Q1
t1.4	I	Tholeiite (Pranpur, Dhanoi–Dahisara, Likhi Hill, Wamoti Moti, Fig. 2a)	Porphyritic with microphenocrysts of plagioclase (An_{60}) set in a groundmass made up of plagioclase, clinopyroxene, ilmenite and glass	Tholeiitic basalt
t1.5	I	Dolerite dyke (Lakhpa–Khatieu, Keera Dongar, Dinodhar, Ranadada, Fig. 2a)	Porphyritic varieties have phenocrysts of plagioclase ($An_{60–65}$) set in a groundmass composed of clinopyroxene (augite), ilmenite. Medium grained nonporphyritic varieties have plagioclase ($An_{50–60}$), augite, ilmenite and show sub-ophitic and intergranular texture	Dolerite
t1.6	I	Gabbroic pluton and laccolith (Manjal Dome, Dhar Dongar, Kaya Dongar, Fig. 2a)	Coarse-grained, hypidiomorphic, almost equigranular with plagioclase ($An_{64–70}$) and augite. Ilmenite is a common accessory mineral with occasional magnetite	Gabbro
t1.7	II	Alkali basalt plug (Dinodhar, Vithon, Dhrubia, Bhujia, Sayara, Nakhatrana, Keera Dongar, Fig. 2a)	Strongly porphyritic with phenocrysts of olivine ($Fo_{70–75}$). Olivine also occurs as xenocrysts ($Fo_{88–90}$). Titanaugite occasionally occurs as microphenocrysts but is a common mineral in groundmass. Plagioclase (An_{35}) occurs as subhedral laths in groundmass along with olivine, clinopyroxene, nepheline, opaque and glass	Alkali olivine basalt (from normative mineralogy); Alkali basalt–basanite using TAS diagram
t1.8	III	Mafic sill of Sadara	Strongly porphyriticwith phenocrysts of olivine (Fo_{76-88}). Clinopyroxene ($Wo_{50}En_{36}Fs_{14}$), plagioclase ($An_{80–82}$). Phenocryst assemblage constitutes about 60% of the rock. Groundmass (0.1–0.3 mm) contains olivine, clinopyroxene, plagioclase and opaque. Porphyritic and glomeroporphyritic texture common, the groundmass is characterized by intergranular and sub-ophitic texture	Porphyritic dolerite/dolerite porphyry
t1.9	III	Mafic dykes of Kaladongar	Porphyritic with phenocrysts of titanaugite and kaersutite set in a groundmass composed of titanaugite, plagioclase, kaersutite, nepheline, biotite and ilmenite	Foid bearing dolerite (theralite)
t1.10	III	Mafic pluton of Kuran	Coarse-grained with occasional pheocrysts of titanaugite set in a groundmass made up of plagioclase (An_{60}), kaersutite, olivine and minor nepheline	Foid bearing gabbro (theralite)
t1.11	III	Pyroxenite of Nir Wandh	Coarse-grained showing hypidiomorphic and cumulus texture with titanaugite (85–90%), kaersutite, minor plagioclase	Kaersutite bearing pyroxenite
t1.12	III	Gabbroid rocks of Nir Wandh	Coarse-grained, equigranular rock, mesocratic to melanocratic in appearance and composed of titanaugite, zoned plagioclase (An_{55}–An_{75}), kaersutite, alkali feldspar, nepheline and accessory apatite, calcite	Foid monzo gabbro (theralite)
t1.13	III	Dioritic rocks of Nir Wandh	Medium to coarse-grained rock, leucocratic to mesocratic, composed of plagioclase ($An_{38–46}$), kaersutite, titanaugite, nepheline minor biotite, and alkali feldspar	Foid monzo diorite
t1.14	III	Syenite of Nir Wandh	Coarse-grained, leucocratic rocks with alkali feldspar, nepheline, plagioclase, kaersutite, aegirine augite and accessory calcite, apatite	Nepheline syenite

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Table 1 (*continued*)

Group	Rock type (locality)	Petrographic description	Classification after IUGS (Le Bas and Streckisen, 1992)
III	Lamprophyre dyke of Nir Wandh	Strongly porphyritic with megacrysts of kaersutite, titanaugite, olivine set in a groundmass composed of kaersutite, titanaugite, plagioclase alkali feldspar, nepheline, calcite, apatite	Camptonite
III	Fine grained mafic dyke of Nir Wandh	Fine-grained mesocratic with plagioclase (An_{64}), titanaugite, kaersutite, alkali feldspar and analcime	Microgabbro (Teschenite)

sill samples also fall in the basalt field but close to the basalt–basanite boundary (Ray et al., 2006). These samples have a close similarity with total alkali varying from 3.5 to 4.5 wt.%. The Sadara sill is silica undersaturated (SiO_2: 45–47 wt.%) with MgO varying from 9.2 to 10.7 wt.%. Mg# is variable between 64 and 68. TiO_2 is around 2 wt.% but the CaO and total iron contents are higher compared to the continental flood basalts (Wilson, 1989).

The rock types of the Nir Wandh complex have a wide variation of alkali (1.47 to 11.48 wt.%). As a result, most of the samples fall in the basalt field but a few plots in the field of picro-basalt, basaltic andesite, basaltic trachyandesite, phono-tephrite and tephri-phonolite. The tholeiitic basalts and the dykes of Kutch Mainland fall in the fields of basalt and basaltic andesite. Among the different rock types studied here, the number of alkali basalts analysed (36) are comparatively large. These samples can be classified as tephrite-basanite with a few as transitional between basalt and tephrite-basanite.

In bivariate plots for the Island Belt rocks (Fig. 5a–f), CaO and Ni show a positive correlation with MgO, but K_2O, Al_2O_3 and ΣREE show negative correlation. $(La/Yb)_n$ has a positive correlation with ΣREE. These

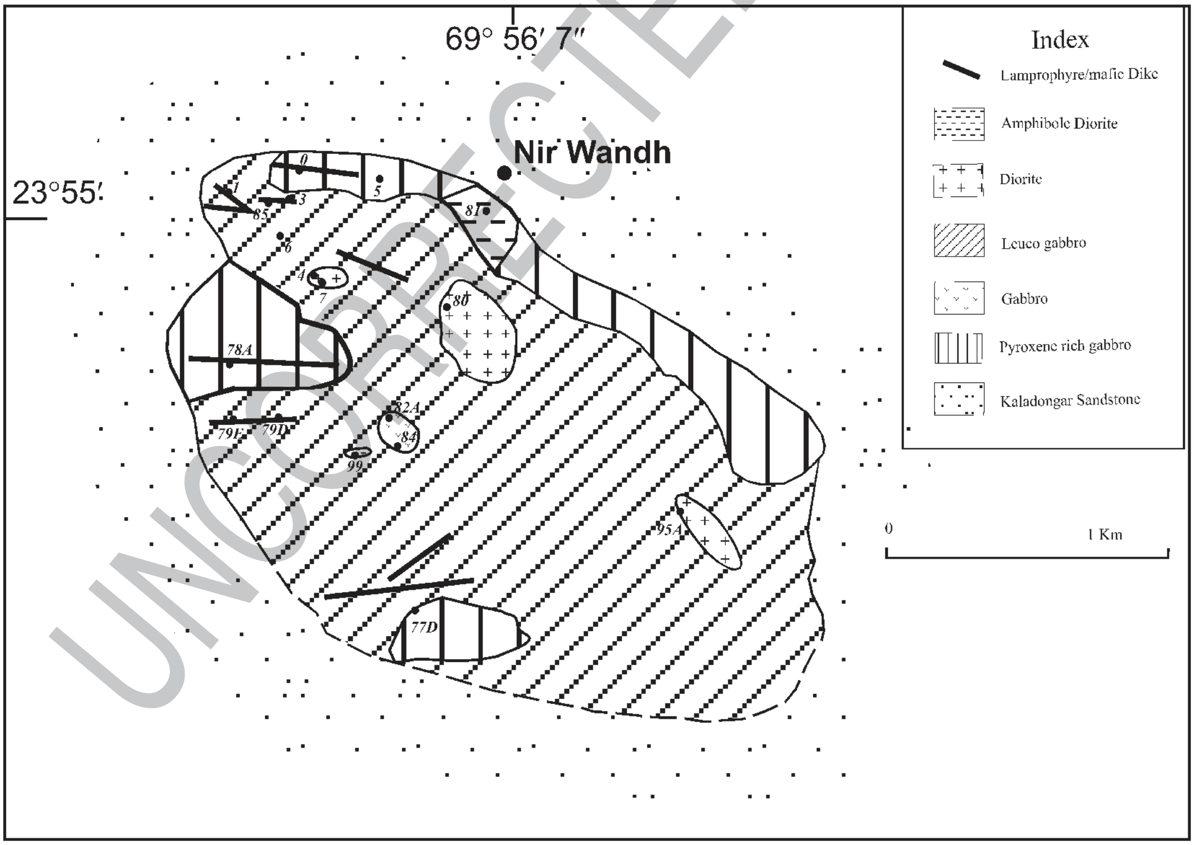

Fig. 3. Geological map of the Nir Wandh Igneous Complex, Island belt, Kutch.

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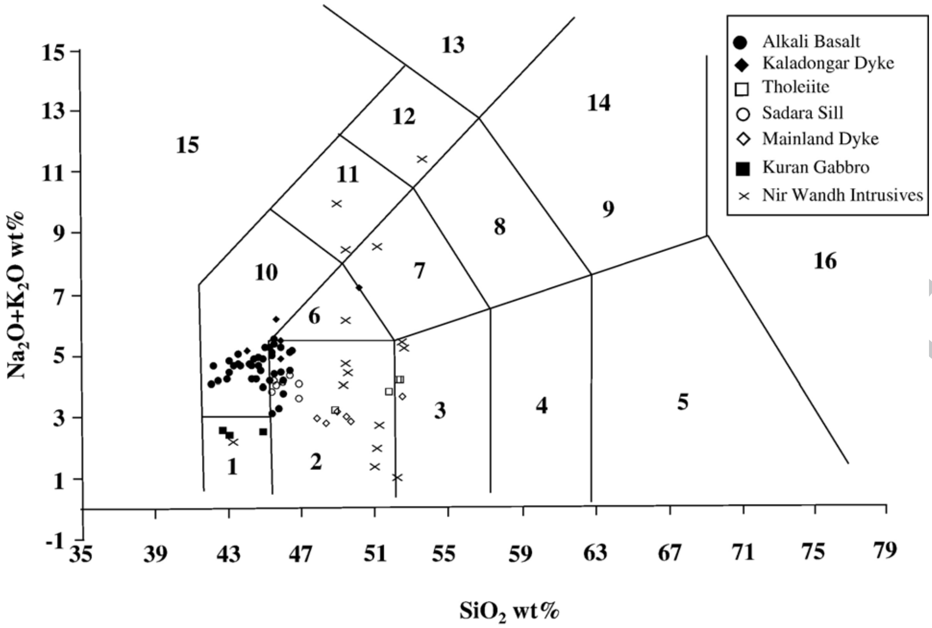
Table 2
Major (wt.%) and trace element (ppm) abundances of representative samples of magmatic rocks, Kutch

Locality	Kala Dongar		Nir Wandh				Nana Dongar	Vithon	Dinodhar	Wamoti Moti	Lodai	Kingriya Dongar	Pranpur	RANADADA	LAKHPA		
Sample	BH32.1	BH33.1	NW-7	NW-85	NW-77A	NW-82A	BH1.1	BH41	BH14.4	BH18.1	LD1.1	BH12.4	BH3.1	BH17.1	BH5.2	JB2	JB2
Rock type	Basalt		Diorite	Pyroxenite	Lamprophyre	Gabbro	Alkali basalt						Tholeiite	Gabbro		Measured	Govindaraju (1994)
SiO_2	43.94	45.54	51.10	42.84	52.48	50.94	42.93	43.47	42.34	44.69	42.07	44.64	51.66	49.57	48.21	52.98	53.20
TiO_2	3.20	2.94	1.05	3.56	2.10	1.64	2.15	2.94	3.21	2.68	3.11	3.01	1.55	0.86	2.41	1.17	1.19
Al_2O_3	12.84	14.18	18.81	11.01	13.43	18.99	11.97	11.80	11.06	10.85	11.69	9.04	13.11	15.28	12.93	14.48	14.67
Fe_2O_3	13.55	13.95	8.53	12.6	11.21	8.78	12.76	14.20	13.68	12.99	12.47	12.51	16.57	12.68	14.43	14.24	14.34
MnO	0.17	0.17	0.17	0.14	0.16	0.08	0.17	0.18	0.16	0.17	0.15	0.15	0.19	0.18	0.18	0.19	0.20
MgO	6.47	6.26	4.33	11.96	4.31	3.15	11.89	10.26	10.21	12.75	11.25	9.11	4.35	6.29	7.83	4.48	4.66
CaO	11.85	8.39	5.50	14.26	6.33	13.50	10.34	10.63	10.89	10.19	9.74	13.72	7.73	12.33	9.22	9.72	9.89
Na_2O	3.29	4.04	6.67	1.36	4.17	1.29	2.89	3.24	2.92	3.32	2.25	2.44	2.97	1.97	2.04	1.99	2.03
K_2O	1.79	2.04	1.97	0.46	1.35	0.18	0.93	1.38	2.98	1.10	2.08	0.87	0.77	0.30	0.67	0.39	0.42
P_2O_5	0.97	1.01	0.49	0.17	0.73	0.05	0.68	0.67	0.47	0.46	0.88	0.98	0.21	0.09	0.33	0.09	0.10
Total	98.07	98.52	98.62	98.36	96.27	98.60	96.71	98.77	97.92	99.20	95.69	96.47	99.11	99.55	98.25	99.73	100.70
Mg#	49	51	54	69	47	46	68	63	64	70	68	63	38	54	56		
Na_2O/K_2O	1.84	1.98	3.39	2.96	3.09	7.17	3.11	2.35	0.98	3.02	1.08	2.80	3.86	6.57	3.04		
Ba	1820	1675	0.19	205.10	0.20	208.90	564.80	466.30	488.60	448.80	3127.00	1371.00	315.20	114.70	157.80	211.30	208.00
Rb	39.06	51.19	85.41	8.00	50.28	6.62	27.15	37.23	53.34	29.35	77.02	67.70	24.54	10.44	14.90	5.99	6.20
Sr	1416	1220	0.64	393.30	0.30	0.89	603.60	981.20	617.20	593.00	1545.00	1942.00	211.40	131.10	192.60	172.40	178.00
Y	31.79	31.17	40.76	17.20	24.61	10.99	22.15	32.48	24.57	20.98	23.23	28.36	41.98	24.45	34.44	24.66	24.00
Zr	288.40	347.50	398.40	137.20	306.50	82.00	189.00	292.80	234.00	224.40	284.60	352.70	164.30	77.60	172.00	51.10	51.40
Nb	101.95	102.56	135.81	26.80	12.64	11.13	63.23	66.40	55.98	59.78	95.34	149.56	20.21	5.92	16.29	0.79	0.80
Th	8.14	10.53	11.45	1.04	7.22	1.24	6.74	6.90	4.28	5.26	9.75	12.33	4.20	1.70	1.95	0.34	0.33
Pb	23.00	7.78	8.24	7.90	4.53	2.74	18.18	9.98	21.94	22.64	7.49	19.83	19.70	18.04	22.63	5.49	5.40
Ga	34.19	33.59	48.35	15.20	43.52	24.31	19.17	25.03	21.80	20.35	46.80	16.79	20.06	17.03	21.80	17.19	17.00
Zn	194.70	222.50	66.60	130.70	195.40	101.70	189.60	192.60	239.90	199.10	220.10	250.60	153.80	102.40	186.20	116.20	110.00

Cu	120.80	80.74	1.03	57.70	48.50	49.50	102.00	79.30	89.30	95.10	72.90	79.20	223.20	148.50	239.20	231.70	227.00
Ni	48.70	54.70	16.70	82.30	50.20	47.90	260.50	209.50	171.30	447.90	317.70	304.40	28.10	88.60	153.30	14.90	14.20
V	358.50	268.20	5.80	532.10	217.10	389.00	306.90	295.10	329.50	277.90	232.10	205.10	399.10	302.80	377.60	586.60	578.00
Cr	27.23	53.70	0.85	56.00	73.10	11.45	525.51	388.79	330.63	635.10	326.26	296.96	12.69	217.18	90.69	26.32	27.40
Hf	5.82	6.84	6.85	3.90	4.84	2.31	4.09	6.49	5.25	4.52	5.99	6.75	3.69	1.66	3.90	1.47	1.42
Cs	3.13	3.01	1.44	0.10	4.32	0.09	0.63	0.70	0.70	0.63	0.97	0.95	0.71	0.46	0.20	0.90	0.90
Sc	18.66	16.83	1.82	37.10	12.77	16.80	27.00	29.60	25.50	25.00	19.40	20.70	43.80	44.90	35.50	52.60	54.40
Ta	14.90	13.10	7.60	4.30	0.17	1.73	4.16	8.83	3.95	5.91	11.24	12.09	2.12	1.22	1.70	0.21	0.20
Co	58.40	52.30	35.70	70.90	37.60	62.10	78.20	73.50	69.50	89.80	73.30	73.30	63.70	67.00	72.70	41.50	39.80
U	2.02	1.98	3.66	0.00	1.07	0.26	0.78	1.39	0.61	0.83	1.79	1.71	0.53	0.28	0.31	0.17	0.16
La	62.70	67.55	82.31	13.60	66.26	13.09	41.68	46.79	30.50	33.90	57.84	80.54	19.40	6.60	13.18	2.40	2.37
Ce	125.39	131.27	146.05	34.60	115.64	24.54	79.21	97.16	66.26	71.57	106.63	151.49	40.00	14.53	32.42	6.19	6.77
Pr	12.07	12.23	14.44	4.10	13.74	2.77	7.57	9.77	6.95	7.10	10.02	14.06	4.01	1.57	3.68	0.98	0.96
Nd	60.14	60.04	53.18	24.50	48.94	14.05	39.32	51.65	38.03	39.36	49.83	74.44	21.43	9.38	22.99	6.77	6.70
Sm	10.79	10.25	9.25	5.00	7.61	2.96	7.08	9.78	7.32	6.93	9.33	11.35	4.47	2.34	5.39	2.28	2.25
Eu	3.73	3.56	2.36	1.70	2.70	1.24	2.32	3.42	2.52	2.33	3.37	3.67	1.52	0.81	1.80	0.91	0.86
Gd	11.87	11.42	7.44	5.60	8.70	2.69	7.95	11.25	8.24	7.60	9.77	12.45	6.04	3.33	6.64	3.27	3.28
Tb	1.52	1.45	1.09	0.80	1.07	0.36	1.02	1.55	1.13	0.98	1.21	1.37	1.07	0.60	1.07	0.62	0.62
Dy	6.43	6.22	7.10	3.40	4.82	2.06	4.36	6.83	4.84	4.30	5.12	5.71	5.96	3.62	5.77	3.75	3.66
Ho	1.13	1.11	0.77	0.60	0.93	0.36	0.76	1.21	0.86	0.72	0.84	0.91	1.35	0.80	1.17	0.83	0.81
Er	3.27	3.29	2.58	1.70	2.62	0.86	2.18	3.45	2.36	1.96	2.34	2.57	4.42	2.64	3.59	2.71	2.63
Tm	0.46	0.48	0.33	0.30	0.41	0.09	0.30	0.50	0.32	0.28	0.31	0.33	0.78	0.44	0.57	0.47	0.45
Yb	2.38	2.49	3.38	1.20	2.21	0.50	1.50	2.57	1.62	1.32	1.58	1.54	4.16	2.40	2.99	2.62	2.51
Lu	0.33	0.35	0.54	0.20	0.33	0.10	0.22	0.35	0.23	0.19	0.21	0.21	0.65	0.37	0.42	0.40	0.39
Total REE	302.18	311.70	330.81	97.30	275.97	65.66	195.47	246.28	171.17	178.52	258.41	360.63	115.25	49.43	101.68	34.20	34.26
$(La/Yb)_n$	18.71	19.28	17.26	11.21	21.31	18.49	19.75	12.94	13.36	18.22	25.96	37.02	3.30	1.95	3.12		
Nb/Y	3.21	3.29	3.33	12.51	0.51	1.01	2.85	2.04	2.28	2.85	4.10	5.27	0.48	0.24	0.47		
Nb/Zr	0.35	0.30	0.34	0.20	0.04	0.14	0.33	0.23	0.24	0.27	0.34	0.42	0.12	0.08	0.09		
$^{87}Sr/^{86}Sr$ measured	0.70459±5	0.70472±1															
$^{87}Sr/^{86}Sr$ initial	~~0.7~~	~~0.7~~															
$^{143}Nd/^{144}Nd$ measured	~~0.51~~	~~0.51~~															



1.Picro-Basalt; 2.Basalt; 3.Basaltic Andesite; 4.Andesite; 5.Dacite; 6.Trachy Basalt; 7.Basaltic Trachy Andesite; 8.Trachy Andesite; 9.Trachydacite; 10.Tephrite Basanite; 11.Phono Tephrite; 12.Tephri-Phonolite; 13.Phonolite; 14.Trachyte; 15.Foidite; 16.Rhyolite.

Fig. 4. Total alkali–silica diagram (Le Bas and Streckeisen, 1991) for Kutch magmatic rocks. Analytical data of representative samples are given in Table 2. Full analytical data can be obtained from the supplementary database of the Journal.

suggest fractionation of olivine and clinopyroxene. Among the Island Belt rocks, ΣREE in the Sadara samples (n=7) varies between 160 and 187 ppm and $(La/Yb)_n$ varies between 11.47 and 11.94. There is no discernible Eu anomaly in any of the samples (Fig. 7b). ΣREE in the Kaladongar dykes (224–355 ppm) is higher than that in Kuran gabbro (72 ppm). These mafic dykes have a fractionated REE pattern, $(La/Yb)_n$ varying from 13 to 21 in contrast to $(La/Yb)_n$ values around 5 in Kuran gabbro (Fig. 5f). It is clear that both the Kaladongar dykes and Kuran gabbro are LREE enriched (Fig. 7b).

As the Nir Wandh complex contains a number of rock types, it is instructive to compare the trace element behaviour patterns among them to explore genetic evolution. In bivariate plots of some major and trace elements (Fig. 6a–f) a scatter of points is observed for the Nir Wandh rocks suggesting that a simple fractional crystallisation model is not applicable. ΣREE in the rocks of the Nir Wandh complex varies from 65.7 to 509.4 ppm from pyroxenite through gabbro to lamprophyre (camptonite). $(La/Yb)_n$ varies from 7.34 to 40.4. All the rock types have fractionated REE patterns except the diorites that have an unfractionated HREE or even a slight enrichment of Yb and Lu. The primitive mantle normalised (Sun and McDonough, 1989) trace element patterns (Fig. 7a) for the Kaladongar dykes and Kuran gabbro show positive Ba, Nb, Sr and Zr spikes. The incompatible elements are enriched compared to the primitive mantle and increase from Kuran gabbro through Sadara sill to Kaladongar dykes. In chondrite normalised REE plots (Fig. 7b), the Kaladongar dykes are more fractionated than the Sadara sill and the Kuran gabbro. The chondrite-normalised REE pattern of average Deccan tholeiite (Mahoney et al., 2000) is very similar to that of the Kuran gabbro (Fig. 7b).

In chondrite-normalised REE plots of the fields of the Nir Wandh rocks (Fig. 8), the gabbro field encompasses those of the other rocks suggesting protracted crystallisation. Lamprophyre and mafic dykes have more fractionated and higher ΣREE abundances than the pyroxenite, believed to be the basal member of the complex. The light REE in the lamprophyres of Nir Wandh are much less (La: 22 to 66 ppm) compared to the La abundance of 174 ppm (sample no Yb-1) in the lamprophyres of Murud–Janjira, south of Mumbai, also in the Deccan Volcanic Province (Dessai et al., 1990) (see Fig. 1 for location).

On MORB-normalised plots (Fig. 9a) the Nir Wandh lamprophyre shows enrichment of LIL elements but

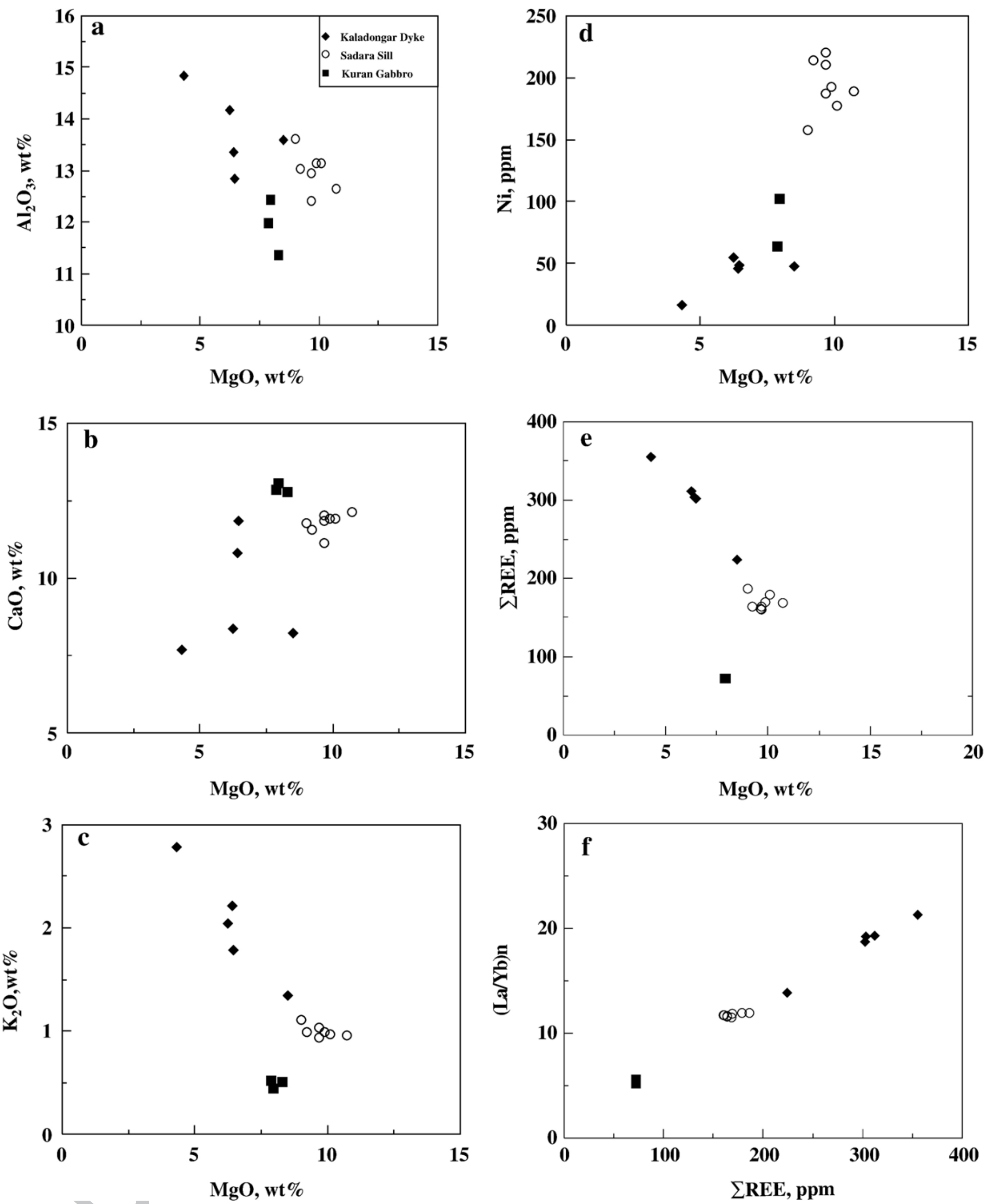


Fig. 5. Bivariate diagram showing Al_2O_3, CaO, K_2O, Ni, ΣREE against MgO for Island Belt rocks, Kutch. In Fig. 5c and e, a negative correlation exists between K_2O and MgO and between ΣREE and MgO respectively. In both the diagrams, Kuran gabbro does not conform to the general trend. A significant positive correlation exists between $(La/Yb)_n$ and ΣREE among all the rock types (Fig. 5f).

compatible and HFS elements show MORB-like levels. In contrast, the camptonites of Murud–Janjira of Bombay coast and Gondwana lamprophyres of eastern India (JC-2) (Fig. 9) show strong enrichments of LIL elements as are typical of alkaline lamprophyres and nephelinites (Le Bas, 1987; Dessai et al., 1990; Rock

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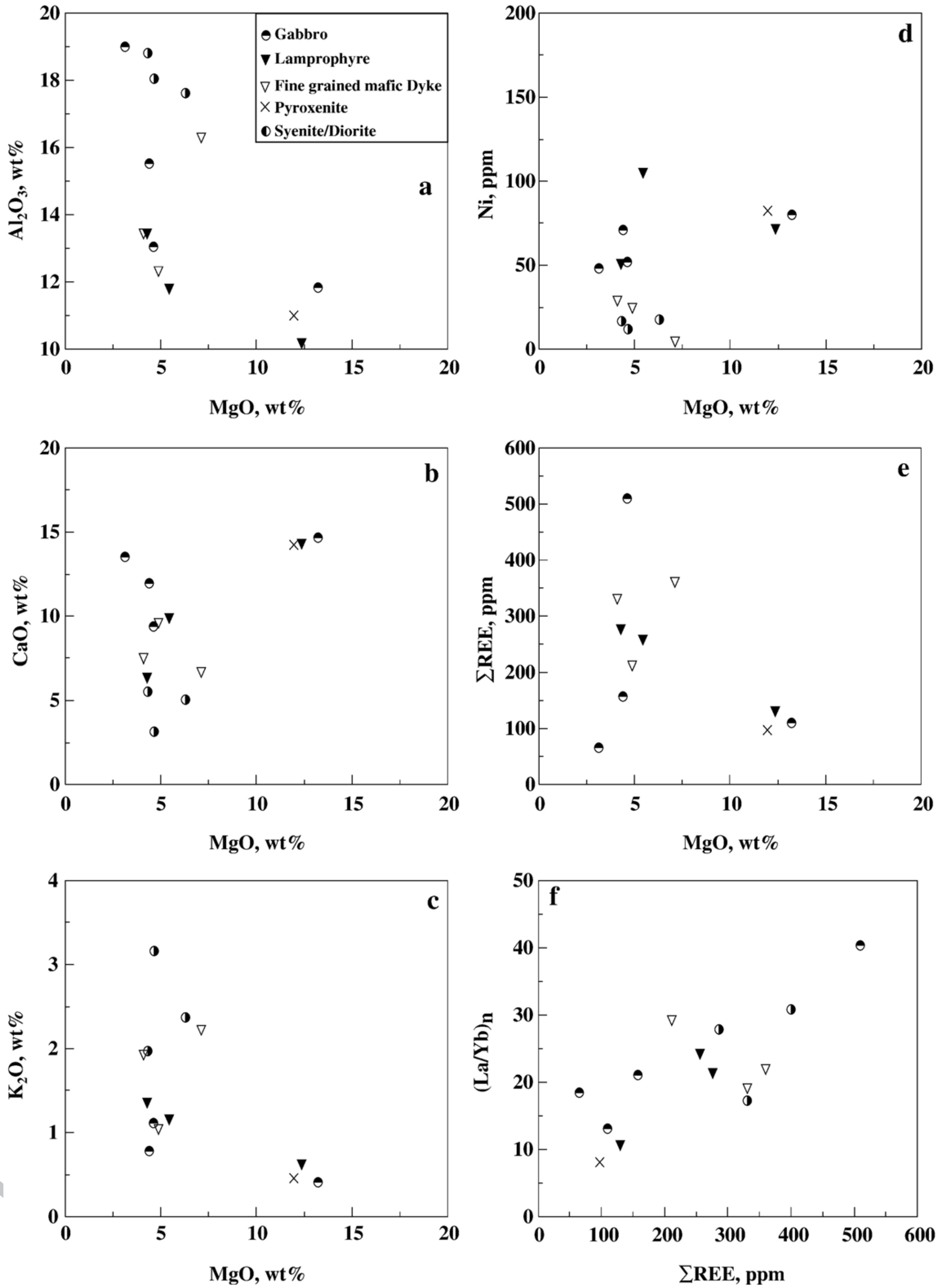

Fig. 6. Variation diagrams of selected major and trace elements against MgO for constituent rocks of the Nir Wandh Igneous complex. Pyroxenite (NW 85), gabbro (NW 5) and lamprophyre (NW 77D) have high MgO compared to the other samples and fall away from the general trends.

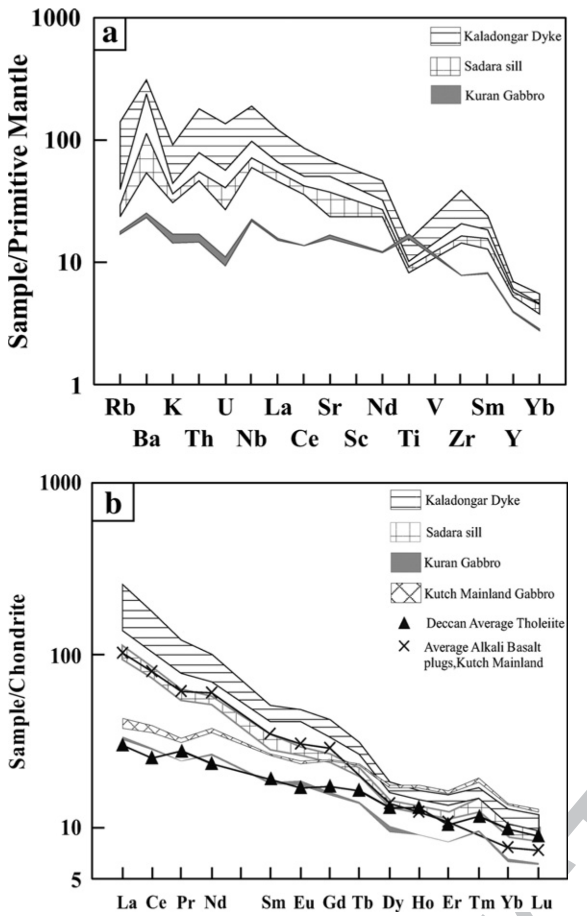

Fig. 7. a: Primitive mantle-normalised trace element patterns (after Sun and McDonough, 1989) for the Island belt rocks. A general similarity among Kaladongar dykes, Sadara sill and Kuran gabbro is seen although there is a significant variation in the incompatible trace element abundances. b: Chondrite-normalised REE patterns for the Island rocks along with the pattern for average Deccan tholeiites (Mahoney et al., 2000); average alkaline basalt and gabbro are from Mainland (this study). Chondrite abundance values are from Evensen et al. (1978).

et al., 1992). These could reflect not only the nature of the enriched source rock as commonly assumed for lamprophyric rocks (see Rock et al., op. cit., for example) but also of the processes of magma generation and subsequent modification by fractional crystallisation.

The variation of Al_2O_3, CaO and K_2O with MgO in the Kutch Mainland magmatic rocks (Fig. 10a–c) show scatter, but Ni (Fig. 10d) maintains a good positive correlation as in the Island Belt rocks. Similarly $(La/Yb)_n$ and ΣREE also has a good positive correlation (Fig. 10f). A role of fractional crystallisation of olivine is clearly indicated. The primitive mantle normalised trace element abundances in alkali basalt, tholeiite and gabbro of Kutch Mainland are similar (Fig. 11a). This pattern is also maintained in the chondrite-normalised REE abundances (Fig. 11b). Plots of Ba and Rb against TiO_2 for the alkali basalts of Kutch Mainland show a continuous variation of TiO_2 from 2.15 to 3.55 wt.% but both Ba and Rb remain more or less constant up to about 2.8 wt.% TiO_2 (Fig. 12). Thereafter, both Ba and Rb increase with increasing TiO_2. The basaltic flows of the Deccan Volcanic Province have been classified into *Formations* based on geochemical criteria (Cox and Hawkesworth, 1985; Beane et al., 1986). Key criteria in the Western Ghats include Sr, Ba, Rb, TiO_2, and Zr/Nb ratios (Lightfoot et al., 1990). Data for the tholeiitic basalt samples of this study (supplementary data base) show high Ba concentrations (182–315 ppm), restricted Sr (211–241 ppm), Rb (24.5–38.6 ppm), low Zr/Nb (2.9–8.1) and low TiO_2 (1.55–2.99 ppm). These characteristics are different from those of the basaltic flows of Mahabaleshwar region (Cox and Hawkesworth, 1985). The criteria used for the classification of the Western Ghats volcanic rocks do not hold in other areas of DVP (Mahoney et al., 2000). Melluso et al. (2006), among others, have shown important lateral heterogeneities in the mantle and a break from the Western Ghats to Gujarat. Therefore, the petrochemical variation observed in the Kutch volcanic rocks is not surprising.

4. Isotopic composition of Sr and Nd

Isotopic measurements were performed on a Thermo Electron TRITON fully automatic variable multi collector mass spectrometer at the Indian Institute of Technology, Roorkee. During the period of analysis, SRM-987 isotopic standard gave a $^{87}Sr/^{86}Sr$ value of

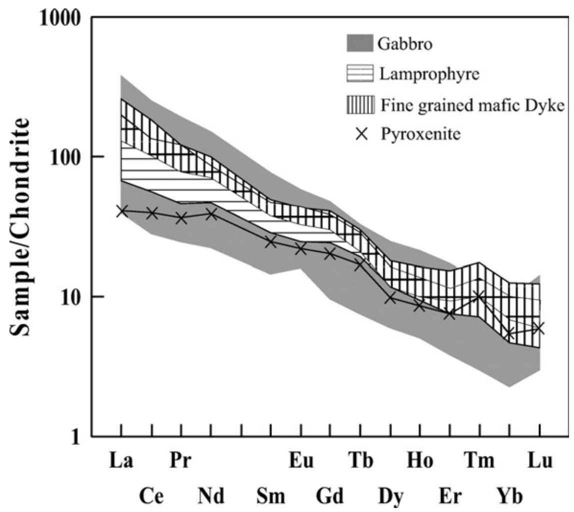

Fig. 8. Chondrite-normalised REE abundances for Nir Wandh rocks. Chondrite abundance values are from Evensen et al. (1978).

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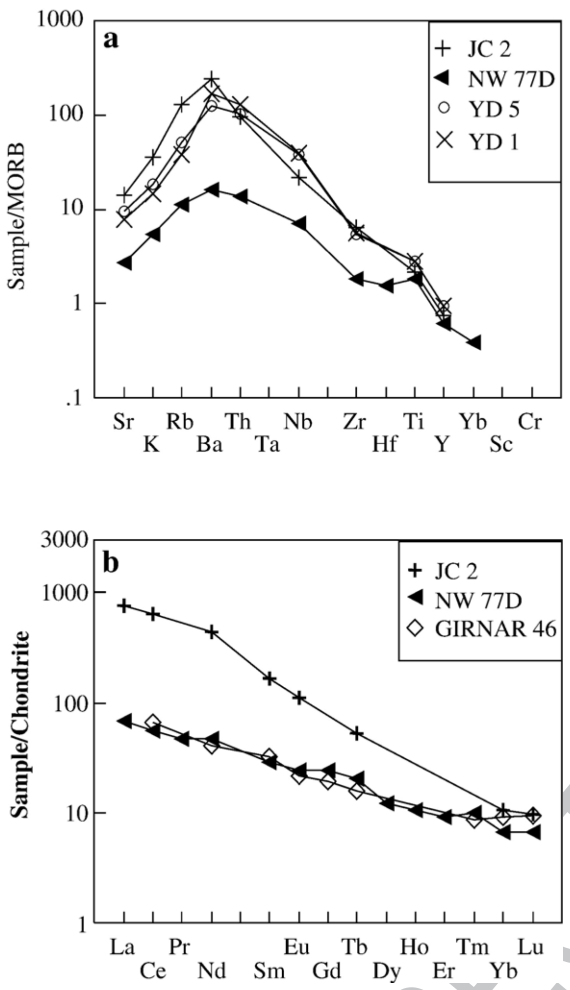

Fig. 9. a: MORB-normalised patterns of selected incompatible trace elements of Nir Wandh lamprophyre (sample no NW 77D) compared with camptonite from Murud, Bombay coast (sample no YD1, YD5; Dessai et al., 1990) and minette (sample No JC 2; Rock et al., 1992) using Pearce's (1983) element order and normalizing values. b: Chondrite-normalised rare earth element pattern of the Nir Wandh lamprophyre (NW 77D; data from supplementary database) compared with that of minette (JC 1) from the Jharia coalfield, India (Rock et al., 1992) and lamprophyre from the Girnar Igneous Complex (Girnar 46; Paul et al., 1977). Normalising values are from Evensen et al. (1978).

$0.710248+10$ (1 s.e, $n=55$) and Ames Nd standard gave a $^{143}Nd/^{144}Nd$ value of $0.512138+4$ (1 s.e, $n=41$). The error assigned is 0.05% for $^{87}Sr/^{86}Sr$ and 0.01% for $^{143}Nd/^{144}Nd$ measurement. The analytical details in respect of the Kutch samples are given in Das et al. (in press).

Measured $^{87}Sr/^{86}Sr$ ratios in the five mafic dyke (Kaladongar) samples vary from 0.70428 to 0.70593; $^{87}Rb/^{86}Sr$ ratios are low (0.016 to 0.127). No isotopic age data is available for the northern Island Belt magmatic rocks. However, assuming an age of 65 Ma (equivalent to Deccan volcanism), the initial $^{87}Sr/^{86}Sr$ ratios are found to vary from 0.70419 to 0.70589. In contrast, $^{87}Sr/^{86}Sr$ ratios in two Kuran gabbro samples are 0.70409 and 0.71065 (see supplementary database; Das et al., in press). The εNd (i) values of the dyke samples vary from +0.3 to −6.5.

In the plot of $^{143}Nd/^{144}Nd$ *vs.* $^{87}Sr/^{86}Sr$ ratios (Fig. 13), besides the Kutch samples, the Bhuj basanites (Simonetti et al., 1998) and the Deccan basalts of Western Ghats (Lightfoot and Hawkesworth, 1988) are also shown. The Deccan basalts show a much larger spread in Sr–Nd isotopic composition with two distinct arrays. Among the different flows of Western Ghats, the Bushe flow has the most radiogenic $^{87}Sr/^{86}Sr$ and unradiogenic $^{143}Nd/^{144}Nd$. This is believed to result from mixing between two end members, one Réunion like asthenospheric mantle and another with high $^{87}Sr/^{86}Sr$ but low $^{143}Nd/^{144}Nd$ (Lightfoot and Hawkesworth, 1988). Among the samples of Kutch shown in Fig. 13, a majority has radiogenic $^{143}Nd/^{144}Nd$ but low radiogenic $^{87}Sr/^{86}Sr$, and fall near the Ambenali–Panhala–Réunion overlap. Even allowing for the small number of samples from Kutch, it is clear that these have a restricted Nd–Sr isotopic composition in the context of the Deccan basalts. Five samples of the Kaladongar dykes show a wide $^{143}Nd/^{144}Nd$ but restricted $^{87}Sr/^{86}Sr$. Comparison of the $^{87}Sr/^{86}Sr$ and the Mg # (Table 2) shows a positive correlation. The most radiogenic sample, BH 28.2 with $^{87}Sr/^{86}Sr=0.70595$ is the most mafic (Mg #=59). This is similar to the Bushe but unlike the Ambenali characters. The Kaladongar dyke isotopic composition is likely to be the result of mixing between a Réunion like composition and another component with radiogenic $^{87}Sr/^{86}Sr$ and unradiogenic $^{143}Nd/^{144}Nd$.

The Sr–Nd isotopic compositions of the Kutch samples of the present study and the basanites of Simonetti et al. (1998) seem to reflect a lateral heterogeneity from the Western Ghat Trap mantle to Kutch. From trace element enrichment of high-Ti picrites of Gujarat, Melluso et al. (1995) came to a similar conclusion. The Bhuj basanites have lower initial $^{87}Sr/^{86}Sr$ ratios (0.70357 to 0.70396) and higher initial $^{143}Nd/^{144}Nd$ ratios (0.51281 to 0.51287) compared to the Kaladongar dykes in northern Island Belt. Therefore, the source region for the northern Island Belt rocks would have been enriched in Rb/Sr and Sm/Nd ratios.

5. Paleomagnetic results

Paleomagnetic investigations comprising AF and thermal demagnetisations were carried out on 150 oriented block samples (around 900 cylindrical specimens

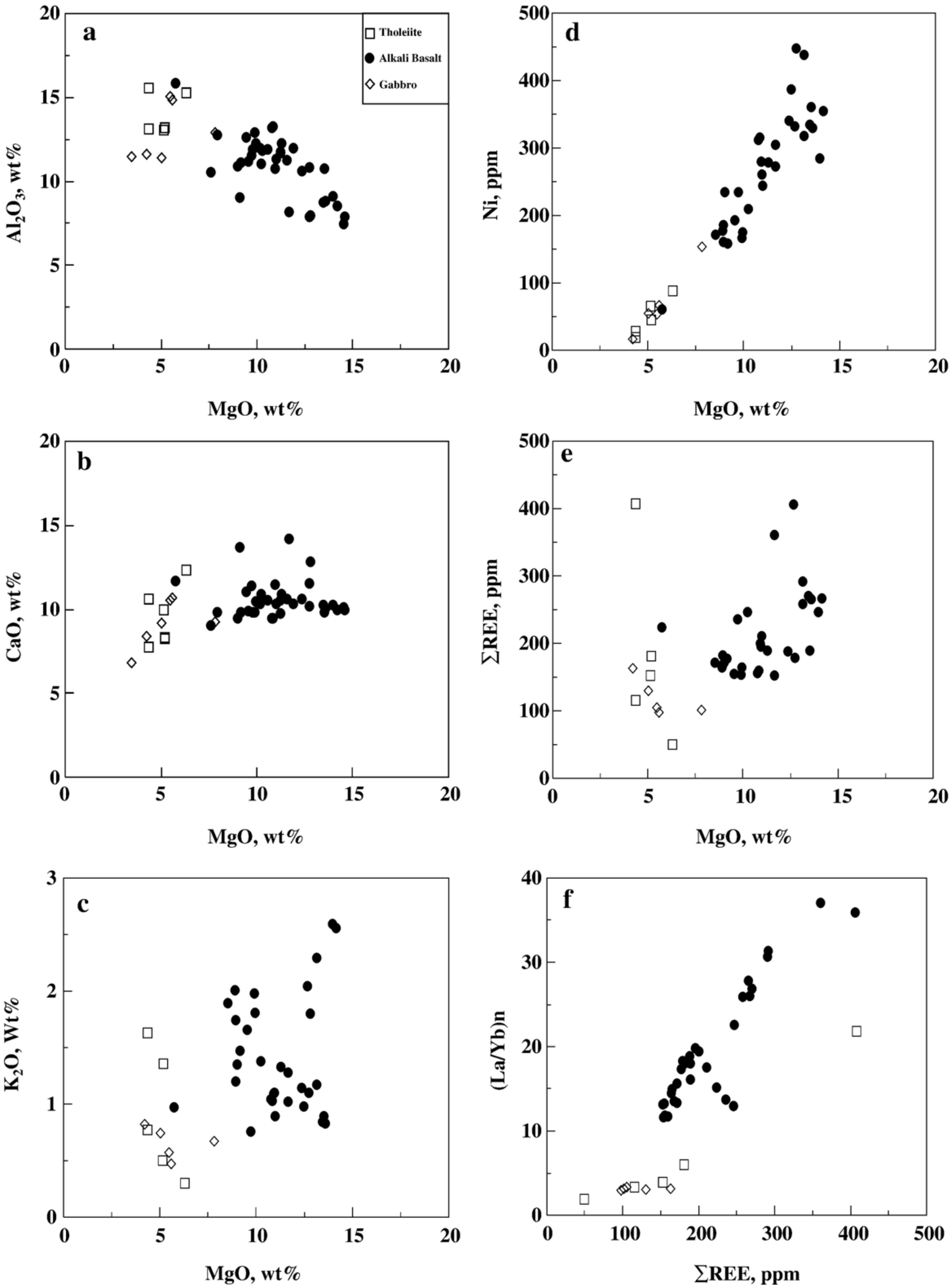

Fig. 10. Variation diagrams of selected major and trace elements against MgO for the rocks of the Kutch Mainland.

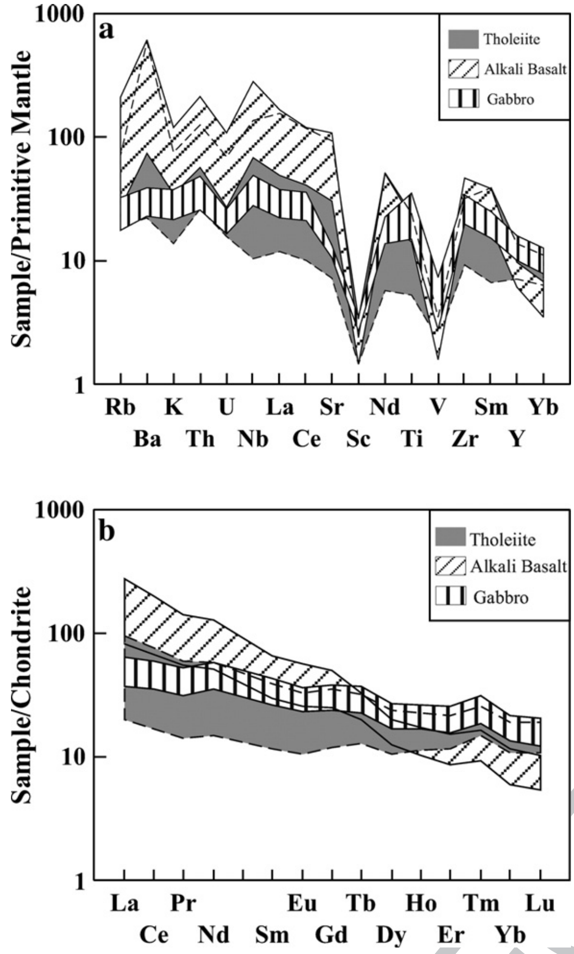

Fig. 11. a: Primitive mantle-normalised trace element patterns (after Sun and McDonough, 1989) for the major rock types of Kutch Mainland. Note the similarity of the distribution patterns. b: Chondrite-normalised REE patterns for the Kutch mainland rocks. Chondrite abundance values are from Evensen et al. (1978).

of 2.5 cm diameter × 2.2 cm length) collected from 30 magmatic bodies/sites (sills, dykes, plugs and flows). Natural Remanent Magnetization (NRM) directions were measured by a JR-5 spinner magnetometer (AGICO, Czech Republic). AF and thermal demagnetizations were carried by a Molspin (UK) AF demagnetizer and MITD-800 thermal demagnetizer (Germany), respectively. Magnetic susceptibilities of the specimens were measured by a MS-2 (Bartington, UK) susceptibility meter.

Based on their spatial proximity, geochemical signatures and mineralogical characteristics, the magmatic bodies were distributed into three groups.

The first group consists of Mainland tholeiite flow sites (Dhanoi, Dhanoi–Dahisara and Pranpur) and Main Land Gabbroic intrusives sites (Kaya Dongar, Likhi Hill, Lakhpa–Khatieu, Dhar Dongar, Ranadada dyke, Habo Dome and Chitrod). The mean Magnetic Susceptibility (MS) values for the tholeiites and intrusives were found as $25{,}073\times10^{-6}$ and $32{,}065\times10^{-6}$ SI respectively. The mean NRM intensities for the flows and intrusives were noted as 9 A/m and 4.58 A/m respectively, whereas the calculated Q-ratios (Koingsberger ratio) for tholeiites and dykes were observed as 10.98 and 5.33 respectively. The stability of the remanence directions in the samples were tested by the application of stepwise AF fields at 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 600, 800 and 1000 Oe and thermal steps of 100, 150, 200, 300, 400, 500, 530, 560, 580 and 600 °C. From the obtained AF and thermal

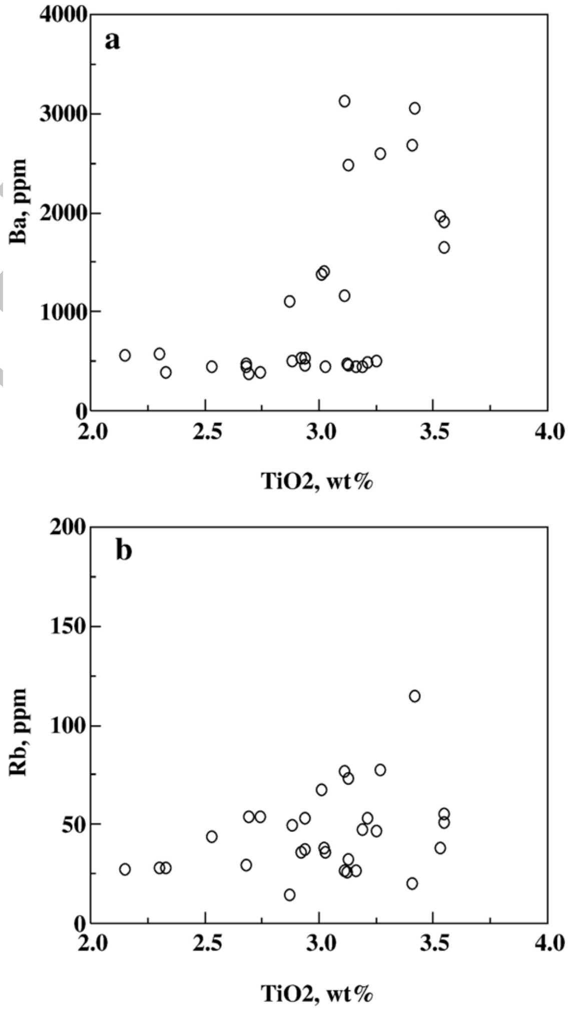

Fig. 12. Plot of Ba and Rb against TiO_2 of alkali basalt of Kutch mainland. A continuous variation of TiO_2 content from 2.15 to 3.55 wt.% is visible. However, the samples can be classified as a high-TiO_2 (>3 wt.%) and low-TiO_2 (<3 wt.%) group. See text for grouping on the basis of other trace elements.

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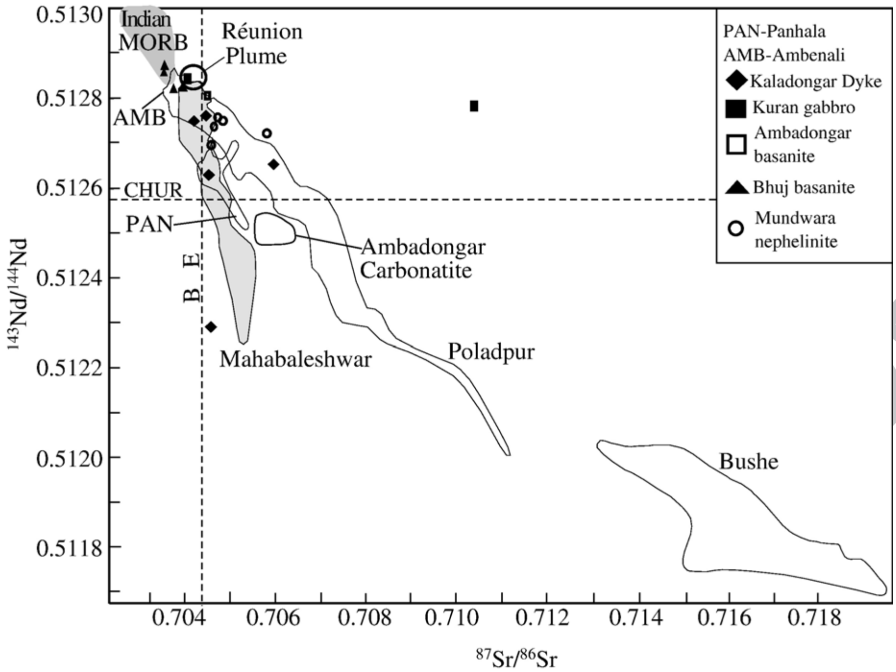

Fig. 13. Nd vs Sr isotope plot for Kaladongar dyke and Kuran gabbro of Kutch (Data: Das et al., in press). Source of other data: Deccan basalt (Lightfoot and Hawkesworth, 1988) Bhuj Basanite (Simonetti et al., 1998). Other fields in this figure are reproduced from Simonetti et al. (1998).

demagnetization spectra, the Characteristic Remanent Magnetization (ChRM) directions were recovered at 250–400 Oe peak AF fields and at 400–560 °C thermal steps. In this group, five intrusive bodies showed 'normal polarity' (north-west declinations associated with moderate negative inclinations) and another two intrusives along with three-flow sites revealed a 'reverse polarity' direction (trending south–east declinations with moderate negative inclinations). From the complete AF and thermal cleanings on the samples of the first group sites, a mean ChRM direction was calculated by using the Fisher's statistics (Fisher, 1953) and the ChRM was noted as $D=336$; $I=-41$ ($\alpha_{95}=13.95$; k= 12.95; $n=10$ sites).

The alkali basalts of Kutch Mainland (12 sites representing Bhujia, Bharar, Kingriya Dongar, Vithon, Dinodhar, Ranadada, Wamoti Moti, Dhrubia Hill, Nana Dongar, Jawharnagar–Kanyaber and Lodai) form Group-II for paleomagnetic study. Magnetic susceptibilities of these sites were found in the range of 9912×10^{-6} SI to 69708×10^{-6} SI with a mean of 34068×10^{-6} SI. The mean NRM intensity and Q ratios were found as 9.27 A/m and 12.29 respectively. The viscous component was erased at and around the temperature of 200 °C and 50 Oe AF steps. The ChRMs were grouped well in the range of 350–530 °C and 50–500 Oe AF fields. Out of the twelve-alkalic basaltic flows, normal polarity was recovered in seven sites and a reverse polarity was isolated in the remaining five sites. The mean ChRM of the second group sites was found as $D=336$; $I=-53$ ($\alpha_{95}=10.28$; $k=20.03$; $n=12$).

Eight sites representing the Kaladongar dyke swarm, Sadara sill, Kuran, Raimarlo Hill and Nir Wandh of the northern Island Belt form Group-III. For this group of samples, higher magnetic susceptibilities (with a mean as $53{,}036\times10^{-6}$ SI units) were observed in comparison to those of Group-I and II magmatic rocks. The mean NRM intensities and Q-ratios for this group were 4.63 A/m and 3.54 respectively, which were found to be lower than those of Group-I and Group-II rocks. The ChRM directions were recovered from all the eight sites through the application of AF and thermal demagnetizations of 400–600 Oe and 400–530 °C windows. From the analyses of the demagnetization data sets, it was observed that two sites (Kuran and Kaladongar) showed a reverse polarity and the other six sites exhibited normal polarity. Normal and reverse polarity signatures in the Kaladongar sites indicate multiple intrusive events for the dykes in Kaladongar. The mean ChRM for the third group was recorded as $D=336$; I$=-40$ ($\alpha_{95}=10$; $k=31.4$; $n=8$).

Antipodal nature of isolated normal ($D=332$, I=-50, $\alpha_{95}=8.23$; 18 sites) and reverse ($D=157$, $I=41$,

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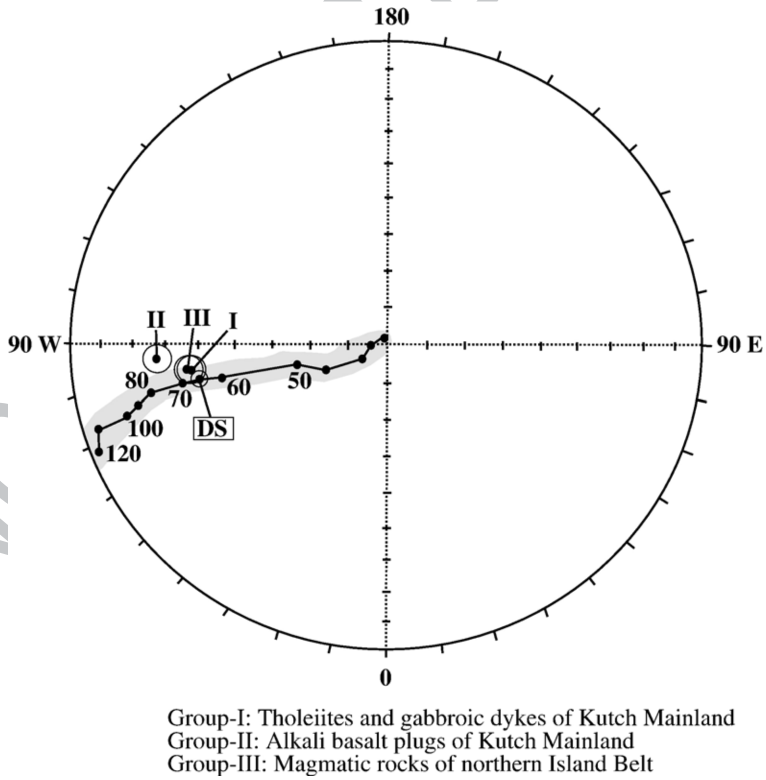
α_{95} = 11.29; 12 sites) polarity directions from the studied 30 sites indicate that the isolated ChRM directions were of primary nature and statistically significant. By converting the reverse polarity directions to normal, the overall mean of all the sites calculated by using the Fisher's statistics was found as D = 335°; I = −45° (α_{95} = 7.5; n = 30 sites) and the corresponding Virtual Geomagnetic Pole (VGP) at 33.7°N and 81.2°W (dp/dm = 5.81/9.18). The obtained pole was found statistically concordant with that of the Deccan Super pole (36.9°N; 78.7°W) as reported by Vandamme and Courtillot (1992). This suggests that the studied Kutch basin magmatic events belong to chrons 30N–29R–29N. However, older ages of the order of 1–2 Ma could be assigned to these magmatic bodies relative to the peak of the Deccan magmatic event of 65 Ma, as there is a 3° difference between the VGP latitude of the samples of the present study and the Deccan Super pole VGP latitude. Further, we have calculated VGPs for the three groups separately. The VGPs for the three groups were found as: 37.6°N:277.4°W (for Group-I), 27.8°N:273.2°W (for Group-II) and 37°N:277°W (for Group-III). The obtained VGPs are plotted along with the Deccan Super pole (Vandamme et al., 1991) on the synthetic APWP (Apparent Polar Wandering Path) in Fig. 14. From the figure it can be observed that Group-I and Group–III magmatic rocks (Kutch Mainland tholeiites and gabbroic dykes and the northern Island Belt) and the Deccan Super (DS) pole were grouped at the 65 Ma part of the synthetic APWP. However, the Group-II (alkali basalts) VGP was found around 70–75 Ma part of the synthetic APWP, indicating that these Group-II rocks are relatively older than the Group-I and Group-III rocks. Available ^{39}Ar-^{40}Ar ages of the tholeiites are 65 Ma against the ages of 68 Ma for the alkali basalts (Pande et al., 1988). However, absolute age determinations of the Kutch magmatic bodies will be helpful in determining the span of the magmatic episodes.

6. Discussion

6.1. General comparison of the magmatic rocks of northern Island Belt and Kutch Mainland

Significant variation among the magmatic rock types such as alkali basalt, picrite and differentiated mafic complexes in Gujarat compared to the overall tholeiitic



Q2 Fig. 14. Groups I, II and III Kutch magmatic bodies and Deccan Super pole (DS) VGPs are plotted along with the synthetic APWP for India (Vandamm et al., ~~1990~~2).

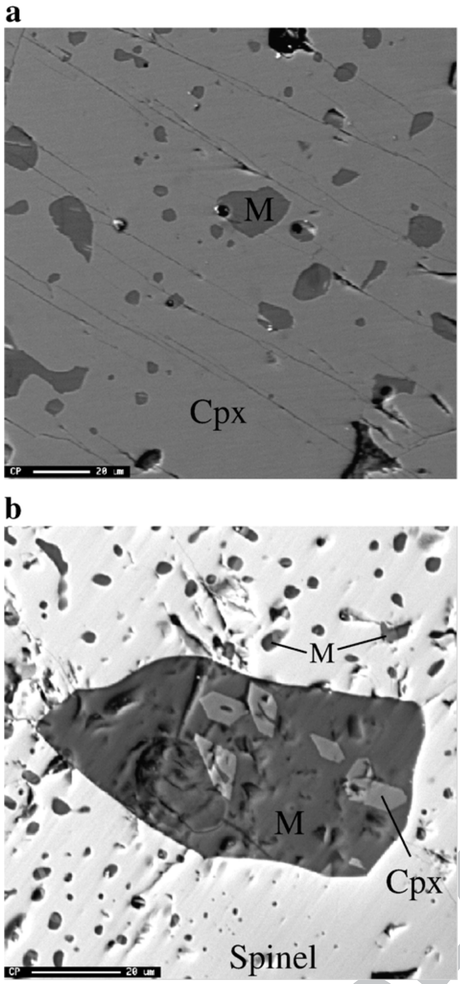


Fig. 15. Photomicrographs showing melt inclusions in ultramafic xenolith minerals. a shows melt inclusions in clinopyroxene in ultramafic xenoliths. b shows melt in spinel. Note that small Cpx grains have crystallized out from the large melt inclusion.

nature of the Deccan Volcanic Province has been noted earlier (Krishnamurthy and Cox, 1977; Mahoney, 1988; Melluso et al., 2006). The present study has further documented the occurrences of mildly alkaline gabbro, basanite, and camptonite from Kutch northern Island Belt. Admittedly, between the northern Island Belt and the southern Kutch Mainland there is a stretch of 80 km with no magmatic rock exposure. However, when we compare the general chemical features of these two belts (Fig. 7b) we note that the chondrite-normalised REE plots for Sadara sill (data from Ray et al., 2006) and the alkali basalt plugs are similar. Between the Kutch Mainland gabbro and Kuran gabbro (northern Island Belt) the REE abundances are similar although the Kutch Mainland gabbro is enriched suggesting that they were derived from similar source in the mantle. Taking the threshold values of 3 wt.% for TiO_2, 1000 ppm for Ba and 50 ppm for Rb, it is observed that the alkali basalt plugs belong to a high-TiO_2, high-Ba and high-Rb (e.g. Lodai, Bhujia, Dhrubia, Bharar, Kingriya), a low-TiO_2, low-Ba and a low-Rb (e.g. Jaksh, Nakhatrana, Dinodhar) group (see Fig. 2a for location of the plugs). Geographically, the former group is in eastern Kutch while the latter is in its western part. The frequency and size of the ultramafic xenoliths are larger in the eastern plugs.

Our paleomagnetic studies indicate that the Group-I and Group-III magmatic rocks (Kutch Mainland Tholeiitic basalts and the gabbroic dykes and northern Island Belt rocks) are grouped at one place and match well with that of the Deccan Super pole. The VGP of the alkali basalts of Kutch Mainland (Group-II rocks) match with the 70–75 Ma part of the APWP (Vandamme et al., 1991). From this, it has been inferred that the Kutch Mainland alkali basaltic plugs of the studied region are relatively older than those of the northern Island and Kutch Mainland tholeiite and gabbroic bodies. Only absolute age determinations will constrain the conclusions decisively.

The geological setting of the Kutch basin has clearly been demonstrated to form as a consequence of rifting (Biswas, 2005). In common with other continental rifts, the magmatic rocks in Kutch constitute a small part of the basin. To draw a parallel, in Kenya, for example, tectonic evolution began with the development of a shallow basin in the Turkana region in the north in Early Miocene (Baker, 1987). Tectonic development of the Kenya rift is usually divided into pre-rift (30–12 Ma BP), half-graben (12–4 Ma BP) and graben stages of development. The nature of volcanism changed from nephelinite–carbonatite through alkali basalt to phonolites. The rock types in the Kutch basin are not as varied. However, in the Kutch region, there is a petrological zonation, north to south, from alkaline intrusives, alkaline basalt plugs to tholeiites. The emplacement of the intrusives in the north has been controlled by the pre-existing rift-related faults.

6.2. Petrogenesis

Within the Deccan Volcanic Province, the Gujarat area in its northwestern part exposes a wide range of rock types ranging from picro-basalts to rhyolites (Krishnamurthy and Cox, 1977; Melluso et al., 1999, 2006). Four distinct petrographic and geochemical magma groups having variable TiO_2 were identified. It was suggested that these were derived from different mantle sources and that there is a strong lateral

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heterogeneity in the mantle, possibly HFSE depleted, beneath Gujarat (Melluso et al., 1999).

Further to the west of Kathiawar in Gujarat, there are ~~also~~ alkaline volcanic rocks, which have recently drawn the attention of many petrologists (Krishnamurthy and Cox, 1977; Melluso et al., 1995; Simonetti et al., 1998; Melluso et al., 2006). The narrow belt of tholeiitic rocks skirting the coast of Kutch has been linked to the Deccan volcanic rocks. However, the alkali basalts and gabbros of the northern Island Belt in Kutch, described in an earlier section, have not been studied earlier except by Maitra (2003). Guha et al. (2005) linked the alkali basalts of Kutch Mainland to the rifting of the Kutch basin. The presence of ultramafic xenoliths in the alkali basalt plugs of Kutch has been mentioned earlier. Karmalkar and Rege (2002) described the petrology of these xenoliths and presented geochemical data of the chromium diopsides from the xenoliths. The depletion of Al, Ti, Ga, Y and HREE with increasing Mg# in diopside, the increase in Ni and Ni/Co with increasing Mg# in olivine and increase in Cr/Al of spinels were believed to be the result of extraction of melt from the source region. Very high concentrations of incompatible elements including LREE in these ultramafic xenoliths reflect an enriched source.

The tholeiite–alkali basalt association in continental flood basalt province has been discussed (Bose, 1980; Devey and Stephens, 1991; Sheth and Chandrasekharan, 1997). The alkaline complexes in the Deccan Volcanic Province occur mostly along the rift zones (Sheth and Chandrasekharan, 1997). The sediment column in the Kutch basin represents the time span from Middle Jurassic to Recent and shows fluvial to marine facies with rapid variation of thickness of sediments. The alkali basalt intrudes this sediment column. Near Nakhatrana (Fig. 2a), Guha et al. (2005) recorded the presence of tholeiitic flows over alkali basalt. In the northern end of the Cambay Graben, Basu et al. (1993) obtained $^{39}Ar/^{40}Ar$ ages of 68.53 to 68.57 Ma for biotites from alkaline olivine gabbro (Mundwara Complex) and from alkali pyroxenite (Sarnu–Dandali Complex). This established that the alkali basalt magmatism in Kutch preceded the major tholeiite magmatism of the coastal belt, which is believed to have extruded at 65 Ma.

Although Devey and Stephens (1991) concluded that large quantities of tholeiite followed by alkali basalt could be generated by varying degrees of partial melting~~.~~ ~~Numerous~~ studies (Francis and Ludden, 1990; Pilet, 2001; Larsen et al., 2003) have emphasized the significance of "metasomatism" for generation of alkali basalt. Mantle-derived ultramafic xenoliths from kimberlites and alkali basalts have documented evidence of infiltration of melts/veins from the deeper asthenosphere, which got frozen at upper levels causing variable enrichment (Erlank et al., 1987). Modal metasomatism records textural change along with formation of hydrous minerals such as phlogopite and kaersutite. However, when the volume of infiltrating melt is low, cryptic metasomatism along with enrichment of selective incompatible elements takes place (Lee et al., 1996; Downes et al., 2004). Selective melting of such enriched zones can generate the Kutch alkali basalt with the observed geochemical characteristics. The geochemical characters discussed earlier have indicated that crystal fractionation, including accumulation of various phases such as clinopyroxene, and olivine has an important role in the formation of the alkaline rocks such as noticed in the Nir Wandh complex.

Silica-saturated, alkali and alumina rich glasses (Fig. 15) are found within clinopyroxene and spinel of wehrlite and lherzolite xenoliths of the Kutch alkali basalt. Karmalkar and Sarma (2003) attributed formation of the silicate glass to the interaction of carbonatitic and silicate fluid coming from the asthenospheric mantle with the orthopyroxene of lithospheric mantle lherzolite. The process has been described as wherlitisation (Yaxley et al., 1997). It is generally agreed that Si–Na–K rich glasses represent a type of metasomatic agent circulating in the upper mantle (Edgar et al., 1989; Draper, 1992). From the geochemical studies of spinel lherzolite xenoliths of Kutch, Karmalkar and Rege (2002) concluded that the lithospheric mantle acquired distinctive features such as LREE enrichment, high Zr/Hf, La/Yb and Nb/La and low Ti/Eu due to interaction of carbonatitic melt and peridotite. We found phlogopite, apatite and calcite in the xenolith fragments and veins of calcite in between olivine and clinopyroxene in wehrlite xenolith. This mineral association further strengthens the idea that an episodic metasomatism occurred in the lithospheric mantle beneath Kutch. Metasomatism was brought about by alkali rich silicate and carbonatitic fluid. The P–T estimate of equilibration from coexisting orthopyroxene-clinopyroxene in spinel lherzolite is of the order of 980°–1060 °C and 9–12 Kb (Mukherjee and Biswas, 1988; Karmalkar et al., 2005).

6.3. Magma emplacement

The rifted nature of the Kutch basin has been documented from stratigraphic and tectonic studies (Biswas, 2005). The rifting and the attendant extension of the Kutch basin may be attributed to thermal thinning of the lithosphere similar to that advocated for the Cenozoic European Rift System (Dèzes et al., 2004). It should be noted that in Kutch there is no magmatic activity in the Early Jurassic when rifting was initiated. Magmatic activity in Kutch was initiated much later. For the melting process to begin, mantle temperature has to be raised above the solidus. This is possible either by asthenospheric up welling or by increased temperature input from a mantle plume.

Various authors have hypothesized that the Réunion plume was generally located at the junction of Cambay rift, Son rift and the Western Ghat rift in western India (Fig. 1) at the time of the main phase of Deccan volcanism (Sen and Cohen, 1994) whose remaining 'tail' is now causing volcanic eruptions on the Réunion Island (Duncan, 1978; Richards et al., 1989; Campbell and Griffiths, 1990). The temperature gradient of the plume head would decrease away from the head, 800–1000 km (Sen and Cohen, 1994; Kerr, 2003) across. If this hypothesis is correct, low temperature fusible constituents in the Kutch lithospheric mantle would have melted first leading to the formation of the low volume alkaline basalt magma in Kutch. Tholeiitic basalt formed later (ca. 3 Ma) due to higher degree of melting. Bouguer gravity data (Raval, 2001) suggest ~~under plating~~ of high-density material perhaps in the form of a large magmatic body in the deep crust close to the mantle in Kutch–Saurashtra–Cambay region (Fig. 1). Such a magmatic body is believed to be the remnant of the lithospheric melt that formed during rift climax (Biswas, 2005). Emplacement of these magmatic bodies in the northern Island Belt took place along the major rift-bounding faults (Fig. 2b) in Late Cretaceous.

7. Conclusions

i. The tholeiitic basalts of southern Kutch have petrological and geochronological similarity with the main eruptive phase of the Deccan Volcanic Province and are considered as the earliest eruptive phase. Hence the mineralogical and geochemical features of these rocks document the onset of volcanism in the Deccan Volcanic Province.

ii. Alkali basalt and alkaline intrusive rocks occur in the central and northern part of the Kutch rift basin. Occurrence of voluminous alkaline rocks as in the present study area is unique in the whole DVP.

iii. Paleomagnetic data indicate close temporal relation between these alkaline rocks and the tholeiitic basalts.

iv. Mineralogical studies and composition of melt inclusions in ultramafic xenoliths (Karmalkar and Rege, 2002; Karmalkar and Sarma, 2003) from the Kutch Mainland alkali basalts indicate that carbonatitic and silicate fluid pervaded the Kutch lithosphere. Low degree partial melting of LILE-enriched lithosphere as a result of heat supply from the Réunion plume generated early primary alkaline magma. Fractionation of olivine and clinopyroxene induced subsequent chemical and mineralogical variation.

v. The source rocks for the magmatic rocks of Kutch is different from the main DVP. This suggests a lateral heterogeneity in the mantle from the Western Ghats to Gujarat.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.lithos.2007.08.005.

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