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Origin and Evolution of the Deep Continental Crust
Editors: N.R. Karmalkar, R.A. Duraiswami, N.J. Pawar and Ch. Sivaji

Petrology, Geochemistry and Petrogenesis of the Magmatic Rocks of Pachcham Island, Kutch, Northwestern India

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Abstract: Western most on-land exposure of basalt of Deccan affinity occurs along the southern coastal belt in Kutch. Abundant magmatic rocks also occur in the Pachcham Island in northern Kutch. These include olivine-clinopyroxene-plagioclase-phyric under saturated basalt (the Sadara sill), gabbro (Kuran), a differentiated alkaline igneous complex comprising pyroxenite, gabbro, diorite and lamprophyre at Nir Wandh and a swarm of basanitic dykes at Kaladongar. Magmatic rocks of Nir Wandh and Kaladongar are characterised by the presence of abundant kaersutite phenocrysts. These rocks are LILE - enriched and have a fractionated REE pattern. Compared to the primitive mantle, the alkaline rocks of Pachcham Island are enriched in K, Ti, alkalis and LREE but depleted in Sc, V, Ni, Cr, Y. There are measurable differences in the major and trace element abundances in the rock types. Paleomagnetic data suggest that the magmatic activity in northern Kutch preceded the Deccan Volcanic eruption, which is generally believed to be in the range 64-67 Ma. Alkaline rocks generally occur in the rift zones in the Deccan Volcanic Province. In Kutch, however, alkaline rocks are common. This is believed to reflect an enriched lithospheric source. The chemical composition was subsequently modified by shallow level fractional crystallisation.

Keywords: Igneous intrusions, Pachcham Island, Kutch, India.

INTRODUCTION

The Deccan Traps of western India covers an area of 500,000 sq km. and is one of the most well studied Large Igneous Provinces of the world. These basaltic rocks have been extensively studied particularly from the Western Ghats (Beane, et al., 1986; Mahoney, 1988; Mahoney et al., 2000; Sen, 2001; Chandrasekharam, 2003, Sheth, 2004 for example). As a result petrologic types and chemical stratigraphy have been established and long distance flow correlation has been made. Within the Deccan Volcanic Province (DVP), Kutch and Saurashtra area in the northwestern part of India exposes a variety of magmatic rock types ranging from picrite basalts to rhyolites via alkaline rocks (Krishnamurthy and Cox, 1977; Chandrasekharam et al., 1999; Melluso et al., 1999; Maitra, 2003; Guha et al., 2005; Melluso et al., 2006). Four distinct magma groups having variable TiO_2 were identified in Saurashtra region. It was suggested that there were strong lateral heterogeneity in the mantle source region beneath Kutch-Saurashtra region. Recent studies by Simonetti et al., 1998; Melluso et al., 2006 for example) have concentrated on the geochemical and isotopic composition of the carbonatites and alkaline rocks of Saurashtra.

The Kutch basin of northwest India (Fig.1) is a pericratonic rift basin. Nagar Parkar uplift in the north and Kathiawar uplift in the south delimit the basin disposition. Rifting in Kutch was initiated in Late Triassic during break-up of Gondwanaland (Biswas, 2005) and was aborted in Late Cretaceous.

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Sample	NW-0	NW-79D	NW-79E	NW-4	NW-7	NW-95A	NW-77A	NW-77D	NW-78A	NW 5	NW-81	NW-82A	NW-84	NW-85
	Fine grain mafic dyke				Diorite		Lamprophyre				Gabbro			Pyroxenite
SiO_2	49.39	52.52	49.35	53.51	51.1	48.83	52.48	42.55	49.51	44.62	49.27	50.94	51.17	42.84
TiO_2	3.09	2.04	1.71	0.96	1.05	1.25	2.1	2.73	3.14	11.83	2.72	1.64	2.08	3.56
Al_2O_3	12.3	13.43	16.28	18.04	18.81	17.61	13.43	10.17	11.78	9.23	13.05	18.99	15.53	11.01
Fe_2O_3	13.06	13.21	10.16	6.08	8.54	9.33	11.24	12.38	13.04	9.23	13.49	8.79	9.86	12.6
MnO	0.16	0.16	0.19	0.12	0.17	0.21	0.16	0.16	0.16	14.68	0.2	0.08	0.12	0.14
MgO	4.89	4.12	7.11	4.67	4.33	6.32	4.31	12.37	5.44	1.61	4.61	3.15	4.39	11.96
CaO	9.57	7.49	6.68	3.14	5.5	5.05	6.33	14.27	9.84	0.41	9.37	13.5	11.96	14.26
Na_2O	3.79	3.4	3.98	8.32	6.67	7.67	4.17	1.9	3.37	1.5	3.03	1.29	2.03	1.36
K_2O	1.04	1.92	2.22	3.16	1.97	2.37	1.35	0.62	1.15	0.34	1.11	0.18	0.78	0.46
P_2O_5	0.77	0.67	0.7	0.43	0.49	0.58	0.73	0.43	0.74	0.34	1.85	0.05	0.3	0.17
Total	98.06	98.96	98.38	98.43	98.63	99.22	96.3	97.58	98.17	97.57	98.7	98.61	98.22	98.36
Mg#	0.47	0.42	0.62	0.64	0.54	0.61	0.47	69.95	0.49	76.95	0.44	0.46	0.51	68.86
Na_2O/K_2O	3.64	1.77	1.79	2.63	3.39	3.24	3.09	3.06	2.93	4.41	2.73	7.17	2.6	2.96
Ba	0.21	0.24	0.15	0.21	0.19	0.07	0.2	233.4	0.33	193.6	0.63	208.9	426.38	486.87
Rb	31.47	84.26	76.4	138.44	85.41	119.14	50.28	12.5	54.39	12	42.41	6.62	36.55	53.75
Sr	0.61	0.87	0.84	0.61	0.64	0.62	0.3	336.2	0.33	493.4	1.38	0.89	1.45	398.3
Y	19.43	36.51	34.99	24.85	40.76	32.45	24.61	21.1	25.19	15.4	47.89	10.99	23.53	27.14
Zr	227.6	408.88	356.81	287.19	398.38	363.43	306.53	165.9	290.66	116.6	200.15	81.95	214.31	212.64
Nb	93.38	171.94	202.39	134.55	135.81	163.21	12.64	38.3	10.77	27	111.57	11.13	39.85	339.62
Th	4.88	11.61	13.52	12.3	11.45	19.1	7.22	2.5	3.74	2.5	11.94	1.24	4.3	9.67
Pb	2.73	4.78	4.74	10.92	8.24	13.69	4.53	8.3	3.22	9.2	1.52	2.74	1.35	0.7
Ga	22.77	34.34	40.43	49.23	48.35	53.35	43.52	16	42.74	13.2	45.73	24.31	30.25	40.24
Zn	69.33	74.57	59.33	48.9	66.63	70.13	195.4	114.2	328.48	72.7	115	101.69	95.46	174.88
Cu	38.49	37.73	20.55	1.78	1.03	0.9	48.49	82.3	78.87	86.5	73.58	49.53	49.91	116.08
Ni	24.34	28.6	4.45	11.87	16.68	17.45	50.26	71.2	104.96	80	51.74	47.86	70.79	183.42
V	226.15	209.15	119.88	18.92	5.81	20.69	217.18	396.3	369.46	198.6	235.73	389.01	393.89	563.08
Cr	47.48	115.53	6.71	1.78	0.85	2.05	190.3	150.8	25.82	11.45	25.16	124.9		
Hf	4.62	7.16	5.13	5.24	6.85	6.05	4.84	4.4	5.39	2.9	3	2.31	4.84	6.9
Cs	0.74	2.89	1.45	1.51	1.44	1.98	4.32	0.2	0.66	0.3	0.67	0.09	0.52	2.07
Sc	11.84	17.61	3.67	3.04	1.82	2.91	12.77	36.1	17.64	38.8	12.09	16.8	23.1	20.29
Ta	6.89	24.87	26.24	7.55	7.6	8.41	0.17	5.2	0.43	2.6	0.17	1.73	3.08	3.65
Co	39.92	42.68	26.24	29.33	35.75	39.58	37.63	70.5	60.04	48.2	56.28	62.12	56.84	66.7
U	0.88	2.08	2.87	3.87	3.66	4.96	1.07	0	0.56	0.02	2.97	0.26	0.8	1.3
La	42.62	74.09	85.96	78.99	82.31	112	66.26	22.3	51.37	20.3	124.23	13.09	32.78	26.76
Ce	88.65	140.87	157.81	130.13	146.05	180.91	115.64	48.6	101.79	43.1	216.84	24.54	62.55	55.43
Pr	8.75	12.94	13.75	11.83	14.44	16.71	13.74	5.2	13.62	4.4	21.73	2.77	6.77	4.65
Nd	44.52	61.99	62.99	41.43	53.18	58.67	48.94	29.4	53.94	23.9	95.05	14.05	32.29	25.43
Sm	7.71	9.98	9.76	6.82	9.25	9.34	7.61	5.8	9.59	4.3	15.53	2.96	6.53	3.91
Eu	2.5	3.33	3.26	1.68	2.36	2.28	2.7	1.9	3.37	1.4	4.46	1.24	2.08	1.05
Gd	8.37	11.27	10.94	5.3	7.44	7.38	8.7	6.7	10.59	5	13.18	2.69	5.61	4.07
Tb	0.99	1.41	1.33	0.72	1.09	0.97	1.07	0.9	1.35	0.7	1.53	0.36	0.73	0.16
Dy	4.07	6.25	5.91	4.43	7.1	5.84	4.82	4.1	5.59	2.9	8.43	2.06	4.14	2.64
Ho	0.64	1.15	1.1	0.47	0.77	0.6	0.93	0.7	0.96	0.5	1.5	0.36	0.74	0.26
Er	1.71	3.46	3.43	1.58	2.58	2.05	2.62	2.1	2.32	1.5	3.9	0.86	1.9	1.32
Tm	0.22	0.53	0.53	0.2	0.33	0.25	0.41	0.3	0.3	0.2	0.39	0.09	0.19	0.05
Yb	1.04	2.76	2.79	2.01	3.38	2.57	2.21	1.5	1.51	1.1	2.18	0.5	1.11	1.69
Lu	0.15	0.42	0.42	0.32	0.54	0.42	0.33	0.2	0.21	0.2	0.48	0.1	0.25	0.05
SREE	211.93	330.43	359.97	285.9	330.81	399.97	275.97	129.7	256.5	109.5	509.42	65.66	157.64	127.47
(La/Yb)n	29.18	19.03	21.88	27.81	17.26	30.86	21.31	10.54	24.21	13.09	40.4	18.49	21.02	11.21

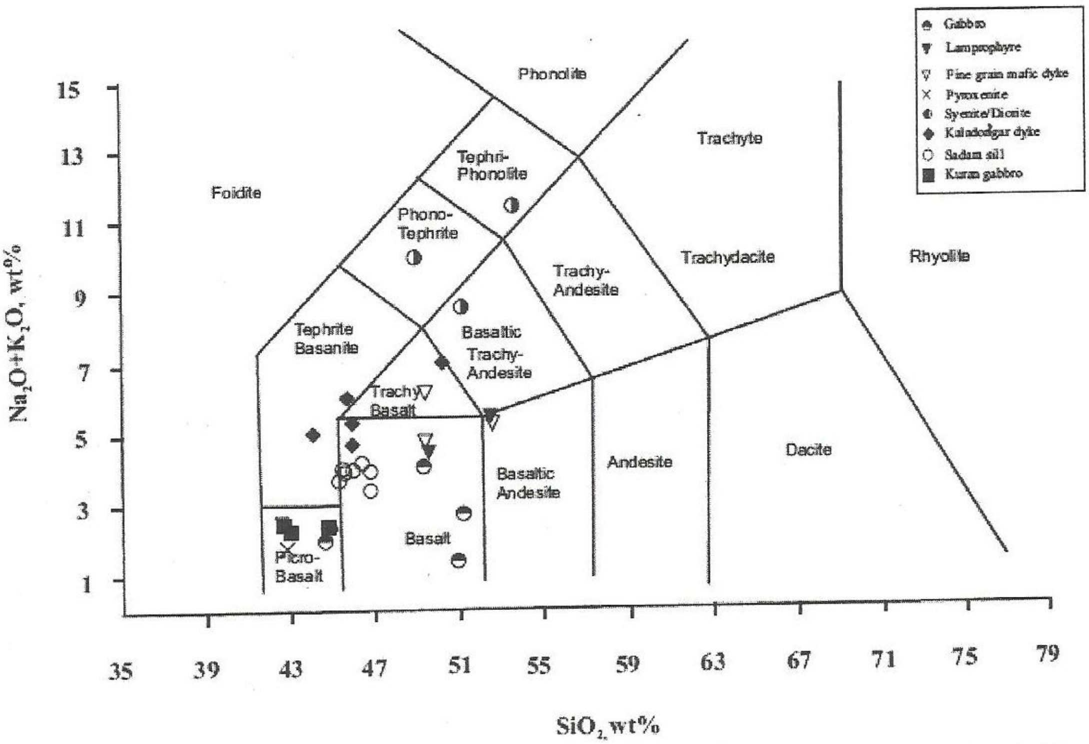

Fig. 5. Total alkali-silica diagram (Le Bas et al., 1986) for the magmatic rocks of Island Belt, Kutch.

Yb)n (Fig. 9d) but total REE shows significant positive correlation with (La/Yb)n (Fig. 9e). K_2O has significant positive correlation with Rb/Y (Fig. 9f). On a Primitive mantle normalized spidergram (Sun and McDonough, 1989) all magmatic rocks of Nir Wandh Complex show more or less similar elemental abundance pattern (Fig.10). Nir Wandh rocks are enriched in K, Ti, Rb, Th, Zr, Sm (10-100 times more abundant than mantle) but depleted in Ba, U, Sr, V and Y (0.1-.01 times). On chondrite normalized REE diagram (Fig.11 a to c) pyroxenite, gabbro, diorite and lamprophyre are plotted separately. In Fig.11d, the fields for REE of the different rock types are compared. While pyroxenite, gabbro and lamprophyre show LREE fractionated pattern, diorite shows a flat REE pattern. None of them shows Eu anomaly.

Among the island belt rocks total REE in Sadara sill samples varies between 160 and 187 ppm and (La/Yb)n varies between 5 to 12. There is no discernible Eu anomaly in any of the samples. Total REE in 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 the Kuran gabbro. Total REE and (La/Yb)n ratio in magmatic rocks of Nir Wandh Complex are as follows pyroxenite around 127 ppm and 11.2 respectively, gabbro 66-509 ppm and 13-40 respectively, diorite 275-400 ppm and 17-31 respectively, lamprophyre 109-256 ppm and 10-25 respectively and fine grained mafic dyke 212-360 ppm and 19-29 respectively.

Lamprophyres of Nir Wandh have been compared with Gondwana lamprophyre from Jharia coalfield (JC 1, Rock et al., 1992) and lamprophyre of Girnar, another differentiated alkaline Igneous Complex from DVP in Gujarat (Paul et al., 1977) on a chondrite normalized REE diagram (Fig.12). All of them show similar REE abundance pattern but lamprophyre of Nir Wandh Complex and Girnar Complex show lesser abundance than the

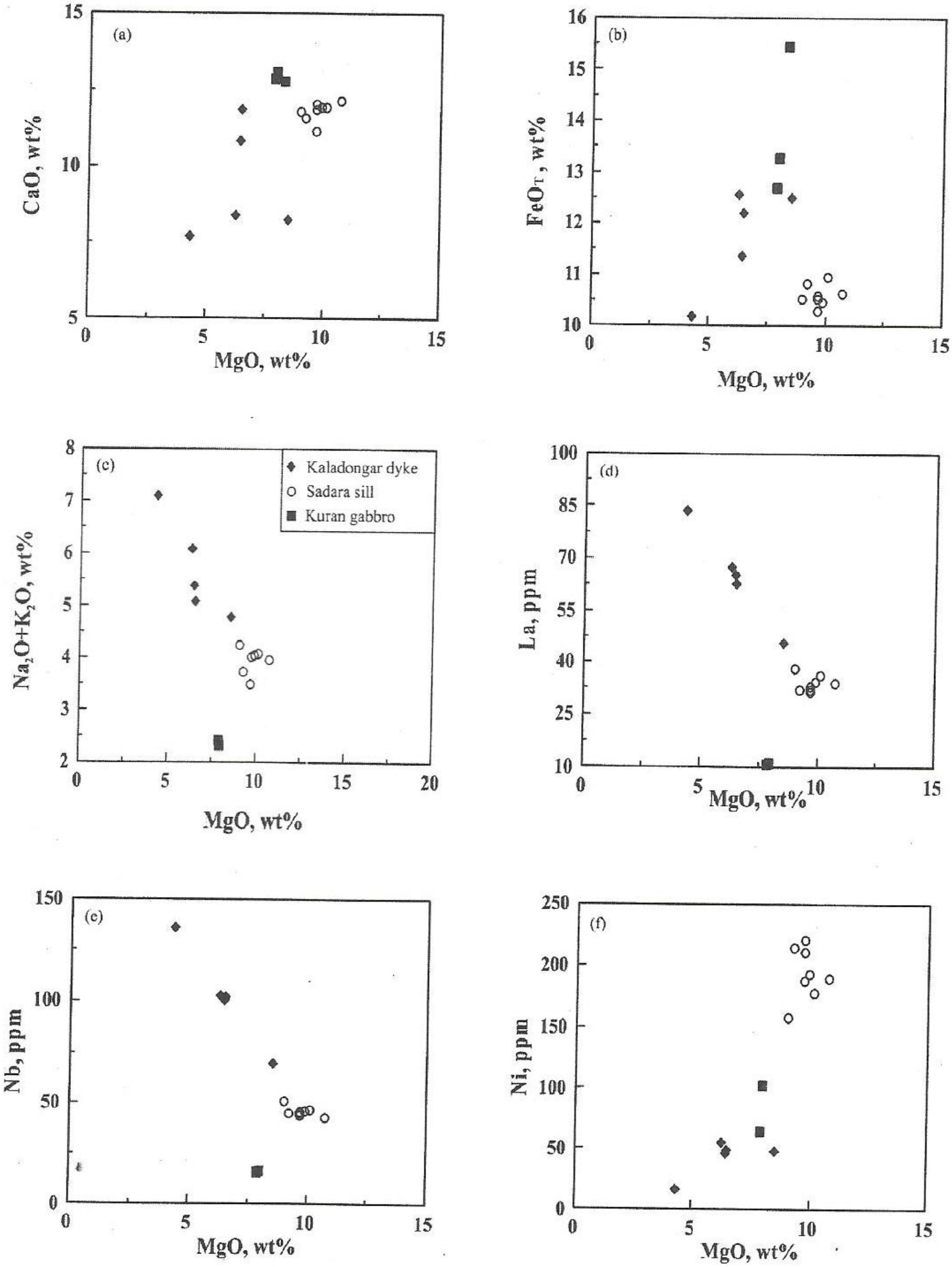

Fig. 6. Biaxial variation diagrams for the magmatic rocks of sadara sill, Kaladongar dyke and Kuran gabbro- (a) variation of CaO against MgO, (b) variation of FeOt against MgO, (c) variation of (Na_2O+K_2O) against MgO, (d) variation of La against MgO, (e) variation of Nb against MgO, (f) variation of Ni against MgO.

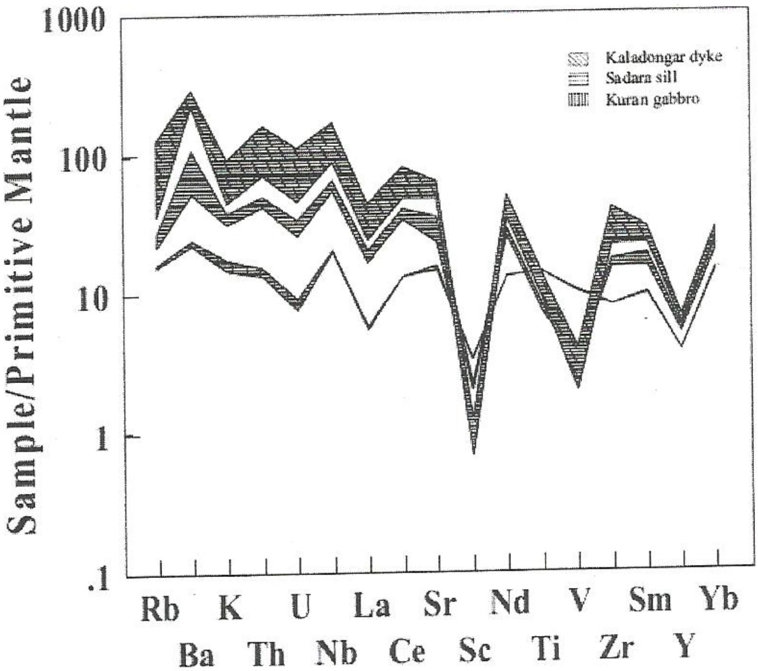

Fig. 7. Primitive mantle normalized trace element pattern for Kaladongar dyke, Sadara sill and Kuran gabbro. Normalised values are those of Sun and McDonough (1989).

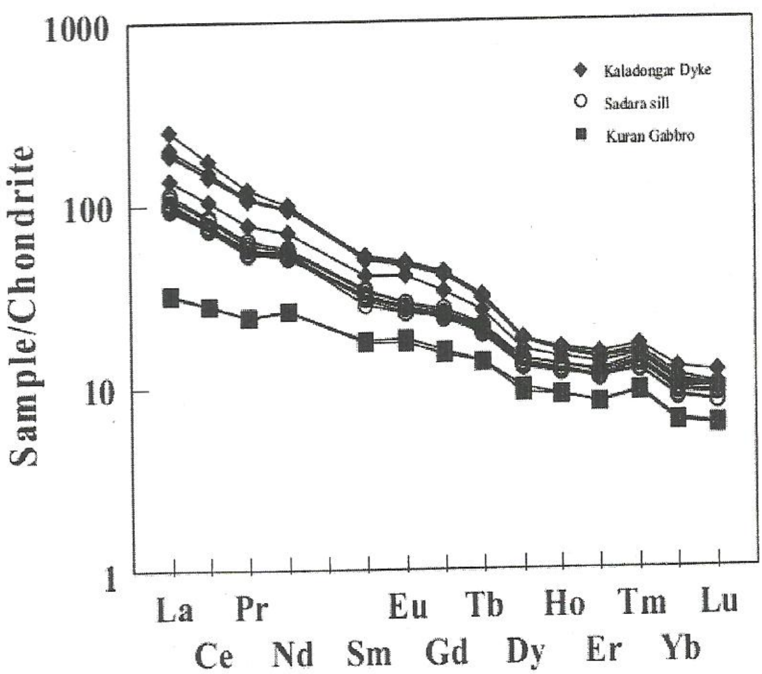

Fig. 8. Chondrite normalized Rare Earth Element diagram showing field for Sadara sill, Kaladongar dyke and Kuran gabbro. Normalising values are from Evensen et.al, (1978).

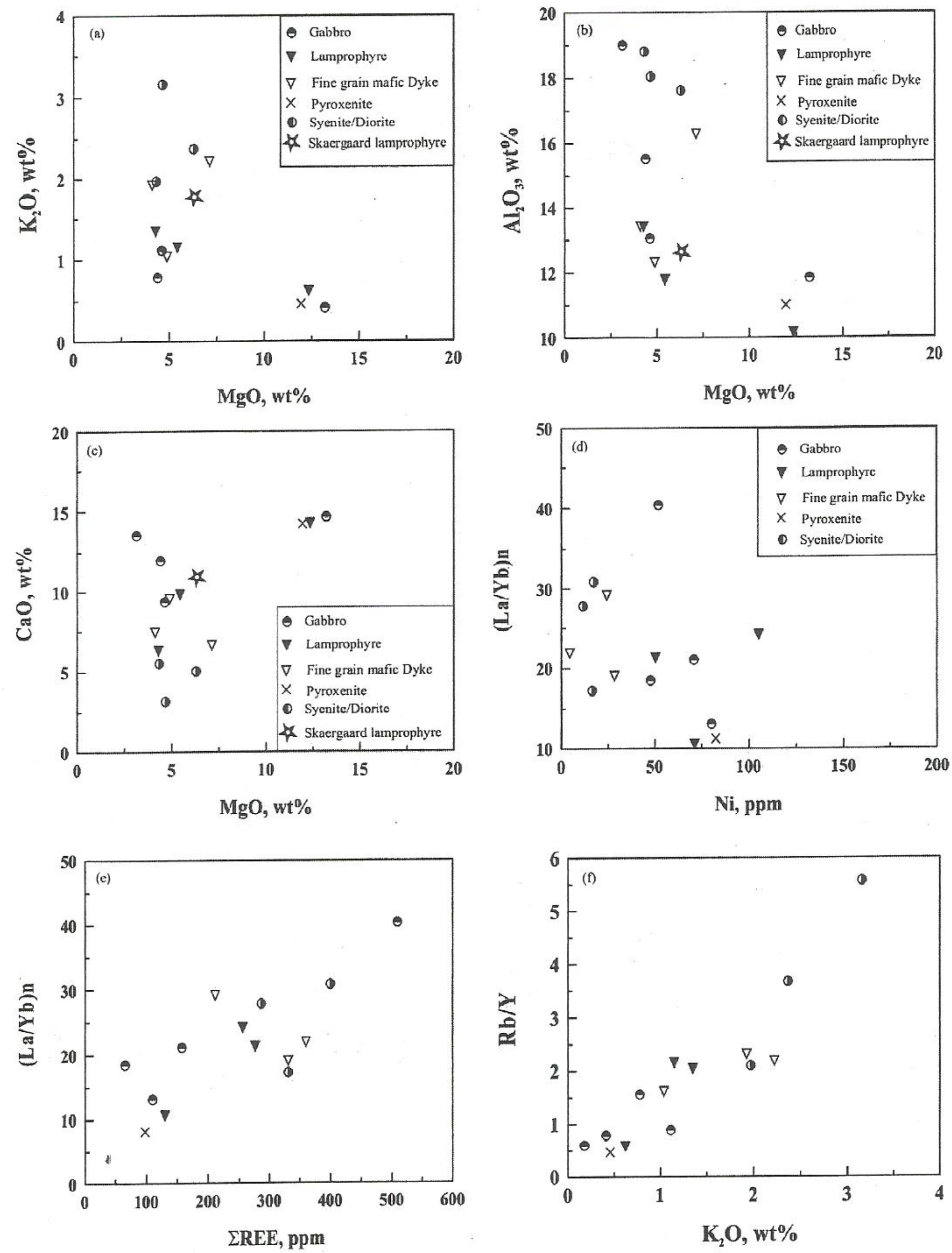

Fig. 9. Biaxial variation diagrams for the magmatic rocks of Nir Wandh Igneous Complex. (a) variation of K_2O against MgO, (b) variation of Al_2O_3 against MgO, (c) variation of CaO against MgO, (d) variation of Ni against (La/Yb)n, (e) variation of Total REE against (La/Yb)n, (f) variation of K_2O against Rb/Y.

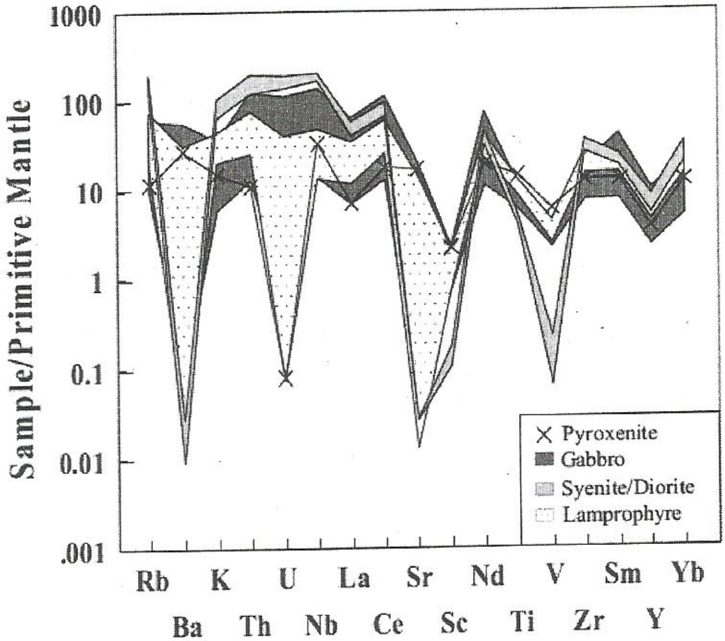

Fig. 10. Primitive mantle normalized trace element patterns for pyroxenite, gabbro, diorite/syenite and lamprophyre of Nir Wandh Igneous Complex. Normalised values are those of Sun and McDonough (1989).

Gondwana lamprophyre. Moreover REE abundances of Girnar and Nir Wandh lamprophyre are exactly same. The light REE in the lamprophyres of Nir Wandh are much less (La: 22 to 66 ppm) compared to the lamprophyres of Murud-Janjira, south of Mumbai, also in the Deccan Volcanic Province (Dessai et al., 1990) (La : 174 ppm).

PETROGENESIS

Magmatic rocks of Pachcham Island in general have alkaline affinity, fractionated REE pattern, LILE enrichment (Figs.7, 8, 10, 11). When all magmatic rocks of Pachcham Island are plotted on bivariate diagrams (Figs. 6, 9) they show a scatter. This possibly indicates continual and periodic replenishment in the magma chamber by addition of fresh batch of magma. Major and trace element variation diagrams for the Sadara sill, Kuran gabbro and Kaladongar dyke indicate progressive enrichment of total alkali, La and Nb with differentiation (MgO depletion) and concomitant depletion of CaO, FeOt and Ni. This is possibly the result of olivine and clinopyroxene controlled fractionation.

In Nir Wandh Complex enrichment of K_2O, Al_2O_3 and depletion of CaO occurs with MgO depletion. Increase of (La/Yb)n with total REE and Rb/Y with K_2O and depletion in Ni with (La/Yb)n also suggest clinopyroxene and olivine controlled fractionation of a parent alkali basic magma. Progressive fractional crystallization of olivine, pyroxene and plagioclase from an alkaline gabbroic melt might be responsible for evolution of Nir Wandh complex. Presence of kaersutite as a dominant phase in gabbro, diorite, syenite and lamprophyre indicate water saturated alkali and TiO_2 enriched nature of the parent magma. The modal proportion of kaersutite increases from gabbro to lamprophyre indicating progressive enrichment of water and other volatiles in the late differentiates due to removal of anhydrous phases like olivine and clinopyroxene. The olivine-

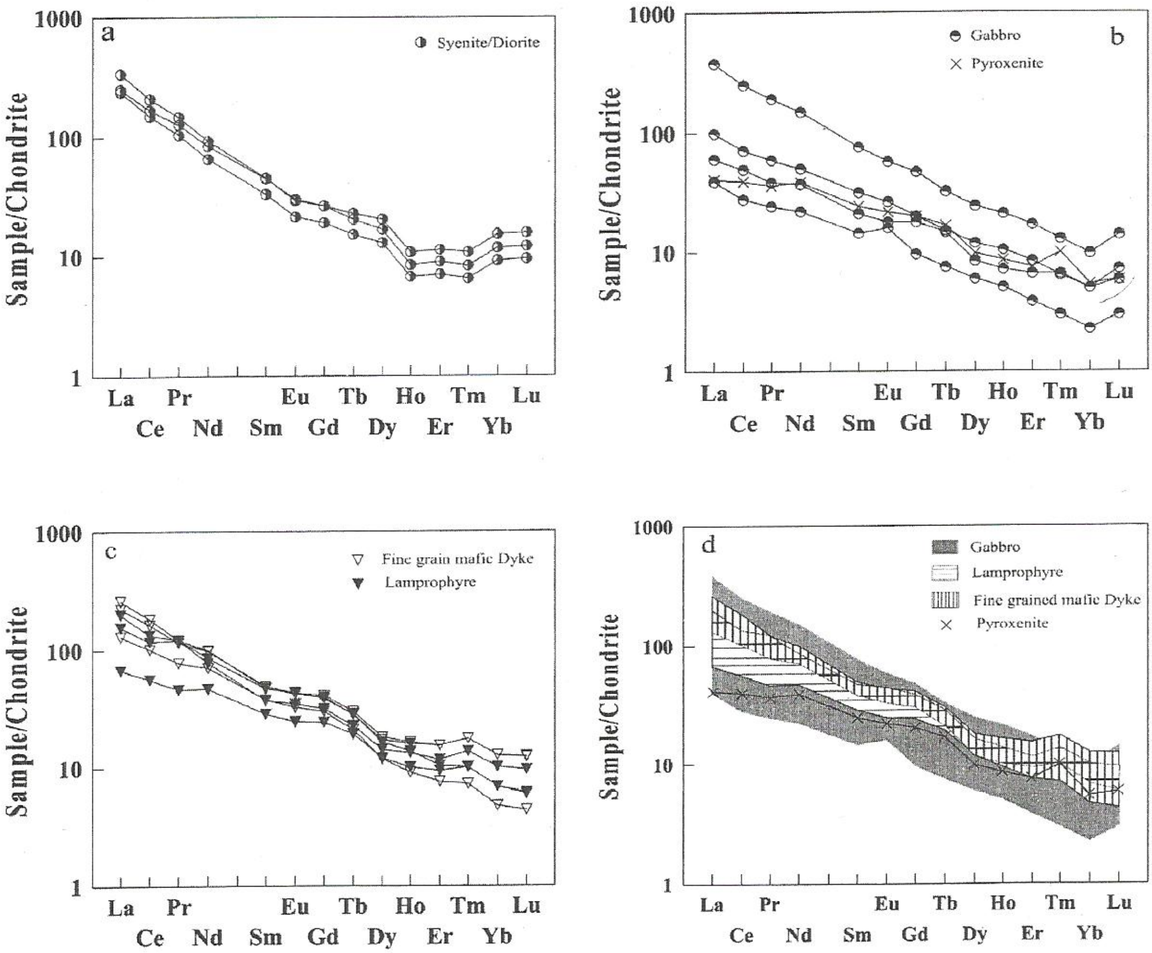

Fig. 11. (a–c) Chondrite normalized Rare Earth Element diagram showing plots of pyroxenite, gabbro, diorite/syenite and lamprophyre of Nir Wandh Igneous Complex, (d) The fields of the above rock types shown together for comparison Normalising values are from Evensen et al., (1978).

clinopyroxene-plagioclase-phyric under saturated basaltic rocks of the Sadara sill is also believed to have formed from an alkaline, LILE enriched, LREE fractionated basic magma and emplaced along zones of intense faulting (Ray et al., 2006).

The mafic dykes of Kaladongar area show a range in composition with Mg# varying from 47 to 59. This indicates that the samples are not primary melts. With the decrease of Mg#, there is a decrease in Ni contents and increase in ΣREE and total alkali (Table1). This indicates the role of fractional crystallization in the evolutionary history of the dykes. However, the general similarity of the trace element signatures in the Kuran gabbro and Kaladongar dykes implies that the characteristics were inherited prior to fractionation. Absence Nb-Ta anomalies (Fig.7) and the general geochemical characteristics (Table1) suggest that significant crustal contamination did not play a role in the genesis of the mafic dykes. Sr-Nd isotopic composition of Kuran gabbro and Kaladongar dyke indicate a

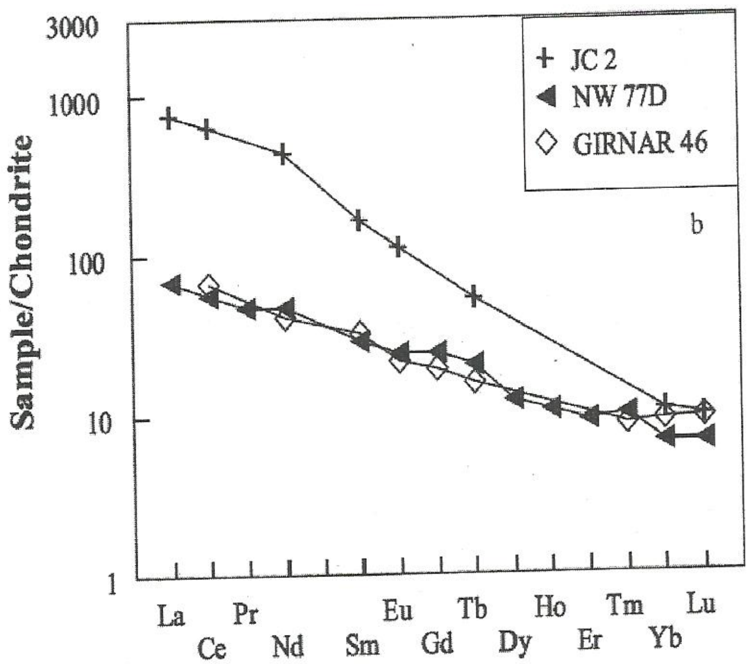

Fig. 12. Chondrite normalized Rare Earth Element normalized pattern of Nir Wandh lamprophyre (NW 77D, data from this study) compared with that of lamprophyre from Jharia Coal field (JC-1, source of data Rock et al., 1992) and lamprophyre from Girnar Igneous Complex (Paul et al., 1977). Normalising abundances values are from Evensen et al., (1978).

mantle source having high Sm/Nd and low Rb/Sr ratios (Das et al. 2007). Assuming the gabbroic magma as the parent melt, the composition of the mineral phases from this study has been used to derive the evolving liquid, represented by the mafic dykes in our case, after ploybaric fractionation using a least square routine (Wright and Doherty, 1970; Stormer and Nicholls, 1978; Andreasen et al., 2004). The calculations show that the gabbro and the mafic dykes can be related by about 42.6% fractionation of clinopyroxene, olivine, plagioclase and ilmenite in the proportion of 67:8:7:18 (Das et al., op cit).

Sub-continental lithosphere beneath Kutch is believed to have been metasomatised (cryptic metasomatism) as evident from study of clinopyroxene of mantle xenoliths and silicate melt inclusion (Karmalkar and Rege, 2002; Karmalkar and Sharma, 2003, Karmalkar et al., 2005). This metasomatism event caused alkali, lime, volatile, LILE and LREE enrichment in the lithospheric mantle. Occurrence of carbonatitic and nephelinitic melt inclusion in Kaersutite phenocrysts of Nir Wandh magmatic rocks and Kaladongar mafic dyke further strengthen the idea of alkali and volatile induced metasomatism of mantle source prior to melting. This fertile mantle could act as source material for the generation of alkaline magma, which on shallow level fractionation of olivine and clinopyroxene gave rise to magmatic rocks of Pachcham Island. Paleomagnetic studies of Sadara sill (Ray et al., 2006) suggest an age of 85 Ma. Kaladongar dykes also indicate older paleomagnetic age compared to the Deccan Trap (Das et al., op.cit). These studies suggest that magmatism in Pachcham Island preceded the main Deccan Trap activity.

CONCLUSIONS

Western most on land exposures of Deccan Traps are found in Kutch. Separated from the southern tholeiitic basalts of Deccan affinity by a sedimentary terrain of about 100 km, there is a northern belt containing widespread magmatic rocks. These include a large basanite sill in Sadara, alkaline gabbro in Kuran, a differentiated Igneous Complex in Nir Wandh and a zone of basanite dyke swarms in Kaladongar. In general, they are alkaline in nature and LILE enriched with a fractionated REE pattern The Nir Wandh rocks and the dykes have a camptonite constituent with abundant kaersutite phenocrysts indicating volatile and Ti-rich source. From the dominant alkaline nature, and compositions of nephelinite and carbonatite melt inclusions in kaersutite the sub continental lithosphere beneath Kutch appears to be metasomatised and enriched in LILE. This is also documented by the study of mantle xenoliths by Karmalkar and coworkers. From the observed geochemical relations in the rocks of the Northern island belt, fractional crystallization of olivine, clinopyroxene seems to have dominant control in the evolution. Our ongoing palaeomagnetic studies in Kutch suggest that the magmatic rocks of the northern belt preceded the main Deccan Volcanic activity. Absolute age determination will help to determine the time span of magmatism in Kutch.

Acknowledgements: We thank the Department of Science and Technology, Government of India for financial support of our Project No DST/23(282)/SU/2001. P.K. Govil and V. Balaram of NGRI, Hyderabad provided analytical support. H.N. Bhattacharya, Head, Department of Geology, Presidency College provided facilities for this research. DKP thanks the Indian National Science Academy for support in the form of Senior Scientist position.

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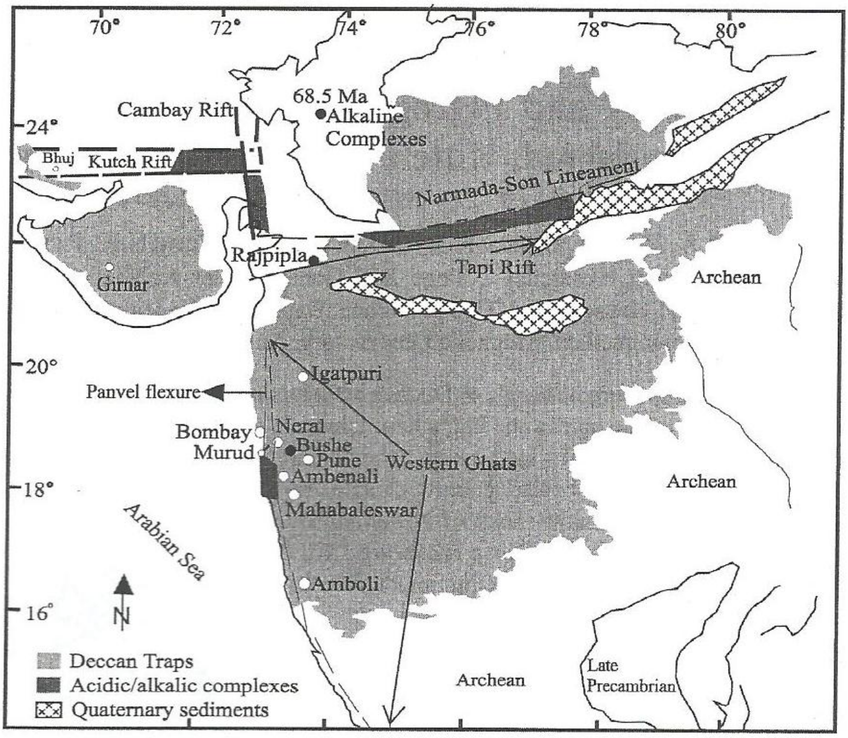

Fig. 1. Map of western India showing Deccan Volcanic Province (shaded area). Location of the present study area in Kutch is shown in the western corner.

Mesozoic sediments fill the major part of the basin. Widespread magmatic rocks, restricted in four uplifted blocks of the northern belt (namely, Pachcham Island, Khadir Island, Bela Island and Chorar Island) (Biswas, 2003). According to Biswas (2003) magmatic rocks of northern island belts represent rift-related magmatic activity. Among the four islands, Pachcham Island has the record of widespread magmatic activity (Fig 2). In Pachcham two intrusive bodies e.g. a gabbro in Kuran (23°56'40" N, 69°47'20" E) and a differentiated alkaline complex (Fig. 3) at Nir Wandh (23°54'20" N, 69°56'11" E) with an intervening zone of alkaline lamprophyric dykes have been reported from the northern belt (Das et al., 2007). Besides, there is a large basanite sill occurring around Sadara intruding the Jurassic sediments (Ray et al., 2006). Emplacement of these magmatic units of Pachcham Island is controlled by tectonics of the basin (Biswas, 1993). Magmatic rocks found in Kutch Mainland Uplift (KMU) in the central part of the basin have been studied by a number of researchers (Krishnamurthy et al., 1989, 1999; De, 1964; Pande et al., 1988, Karmalkar et al., 2000, 2005). Magmatic rocks of KMU are represented by an east-west trending belt of tholeiitic basalt along the coast and another arcuate belt of alkali basalt further north (Fig. 2). These alkali basalt occurs as plugs in the Bhuj Sandstone (Cretaceous) and contain ultramafic xenoliths (De, 1964). Available isotopic ages (Pande et al., 1988) on these tholeiites and alkali basaltic plugs show a span from 64 to 68 Ma, the alkali basaltic plugs showing a slightly older age. Petrologically, the tholeiite has Deccan affinity. No isotopic ages are available so far for the magmatic rocks of northern Island Belt. Magmatic

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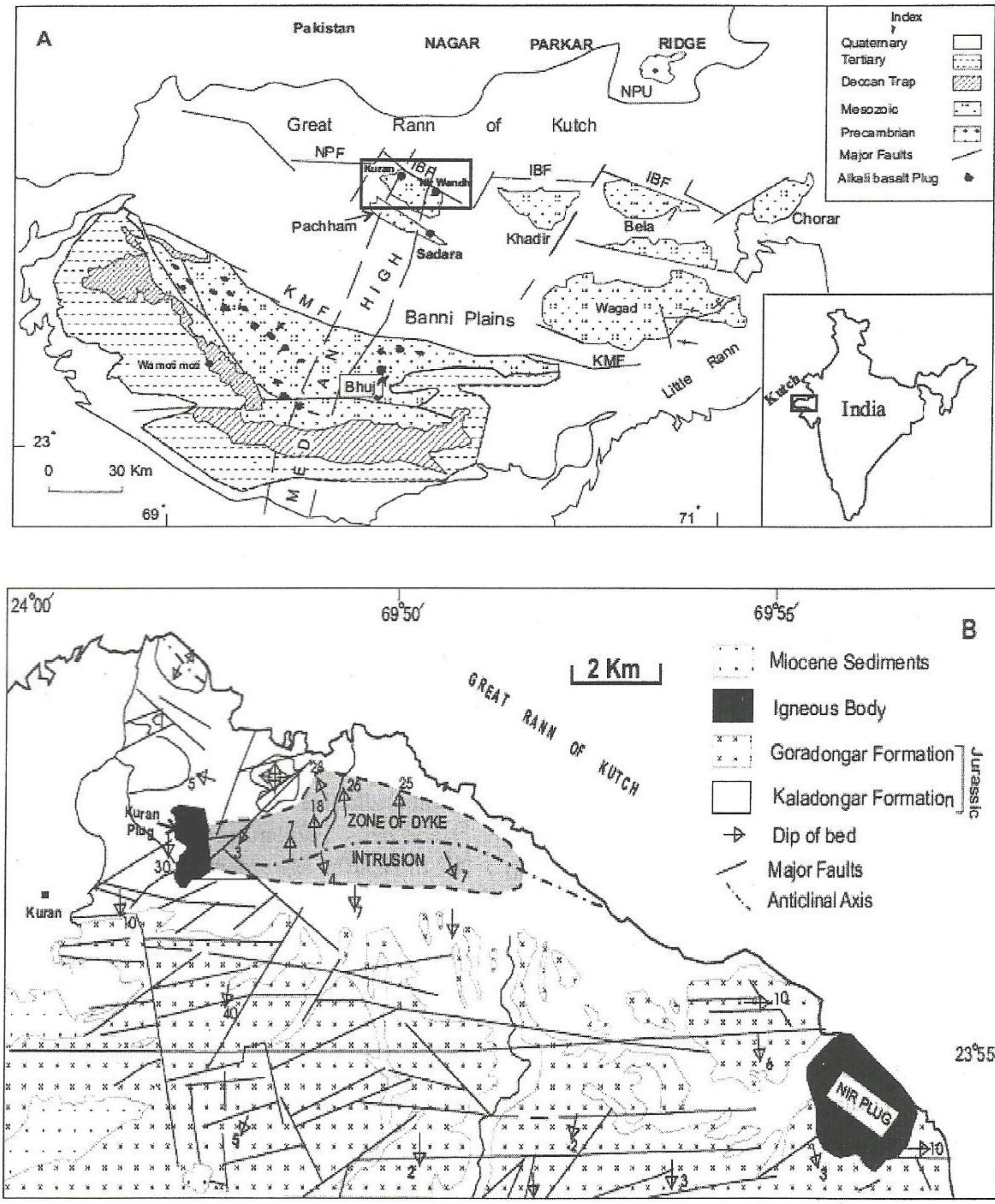

Fig. 2. Geological map of Kutch showing the northern Island Belt magmatic rocks (modified after Biswas, 1980, 1987).

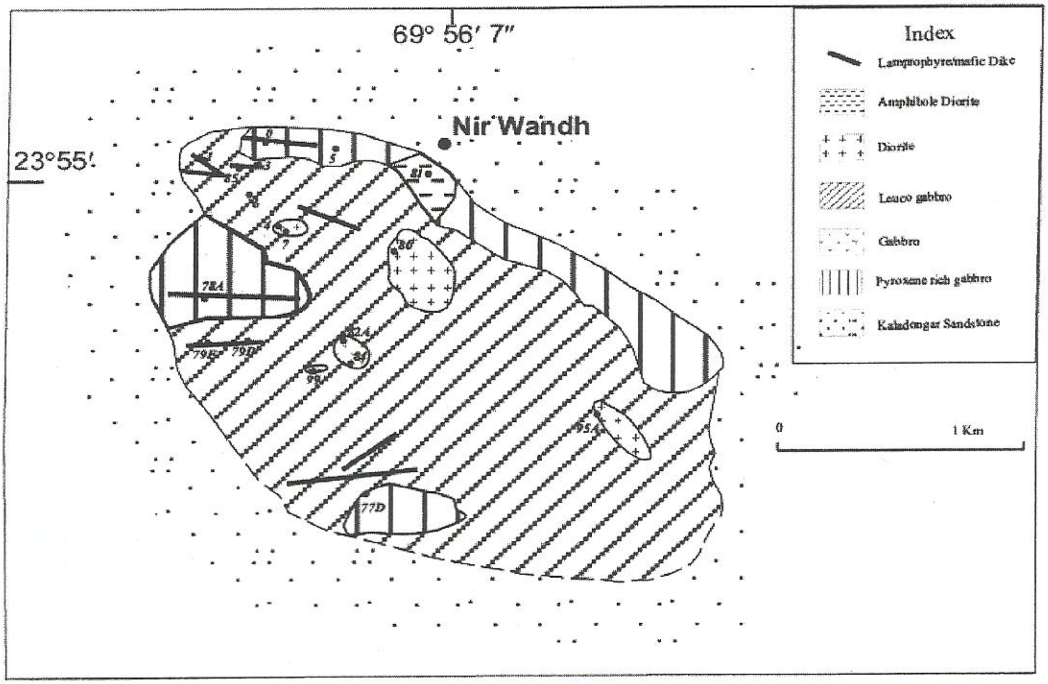

Fig. 3. Geological Map of Nir Wandh Igneous Complex.

rocks of northern belt are separated from the southern magmatic belt by the Kutch Mainland fault (Fig. 2). Magmatic rocks of the northern Island belts occur as dykes, sills and plutons. None of the four island belts contains tholeiite flows and alkali basalt plugs which are fairly common in the southern part (in Kutch Mainland Uplift). Bouger gravity data (Raval, 2001) form the area suggest under plating of high-density material perhaps in the form of a large igneous body in Kutch-Saurashtra-Cambay region.

In the dominantly tholeiitic Deccan Volcanic Province, alkaline rocks are volumetrically small (Bose, 1980). However, alkaline rocks are known from Mount Girnar (Bose, 1973, Paul et al., 1977), Amba Dongar carbonatite complex (Chatterjee et al., 1992), Rajpipla (Mahoney, 1988), Panawad-Kawant (Sukheswala and Avasia, 1972) and around Murud, south of Mumbai (Dessai et al., 1990).

The Kutch basin is unique in the sense that it has rocks of Deccan affinity in the southern part generally linked to Reunion Plume and also rift-related alkaline magmatic rocks in the northern island belts. Paleomagnetic studies on the Sadara sill indicate an age around 85 Ma (Ray et al., 2006). An older age (compared to the Deccan) for basanite dykes of Kaladongar has been reported (Das et al., 2007). In this paper we present petrological and geochemical data on the magmatic rocks of Pachcham Island and discuss their petrogenesis.

PETROGRAPHY

Petrography of magmatic rocks of Pachcham Island can be discussed broadly under three heads

a) Sadara sill:

A mafic sill is exposed in the eastern extremity of Goradongar Hills, north of the village Sadara

(23°45' 14.7" N, 69°53'57" E). The Sadara sill is dark coloured, inequigranular with phenocrysts of olivine, pyroxene and plagioclase set in a mesostasis of finer grained olivine, clinopyroxene and plagioclase with opaque minerals and glass. All three constituent minerals show bimodal size distribution. Among the phenocrysts, olivine (14- 33% volume), clinopyroxene (23-42% volume) and plagioclase (24-45% volume) constitute the assemblage. The phenocrystal phases together comprise about 60% (52%-65%) by volume of the rock. The groundmass minerals are anhedral. The rocks display porphyritic, ophitic-subophitic and intergranular texture. Glomeroporphyritic texture is common where plagioclase grains form aggregates. Intergranular texture with plagioclase microlite enclosing clinopyroxene is also present.

Most of the olivine phenocryst (Fo_{76} to Fo_{88}) grains are euhedral to subhedral. Some of the olivine grains have been altered to serpentine along cracks and some of the olivine phenocrysts commonly show reaction embayment. Most of the larger olivine grains are zoned. The forsterite content in the groundmass olivine (Fo_{55-65}) is also similar to that found in the rims of the phenocrysts. Pyroxene phenocrysts ($Wo_{50.65}En_{35.47}Fs_{13.88}$ to $Wo_{52.12}En_{42.57}Fs_{5.31}$) form short prismatic euhedral grains, while all plagioclase phenocrysts (An_{80-82}) occur as subhedral laths. Pyroxene in the rock is mainly augite (titanaugite) and salite as evidenced by their pleochroic character (feebly pleochroic from light yellow to green) and z^c values around 35°-40°. Pyroxene and plagioclase phenocryst grains are distinctly zoned. Reaction structures and zoning are common in the pyroxenes. Pyroxene phenocrysts are frequently twinned. The symmetric extinction angle of plagioclase varies between 30°-40° indicating labradorite to bytownite compositions. Groundmass plagioclase grains have a rather uniform composition of An_{63-67}. Clinopyroxene is less abundant than olivine in the phenocryst assemblage, but pyroxene is more abundant as a groundmass constituent. The composition of the opaque minerals is Fe-Ti oxide (titano-magnetite). Modal data and composition of constituent minerals are given in Ray et al. (2006).

b) Kuran Gabbro and Kaladongar dyke

Two basic intrusive bodies are exposed in Pachham Island - one at the western part of the Island around Kuran (23°56"403 N, 69°472 203 E) and the other at the northeastern part around Nir Wandh (23°54" 203 N, 69°562 113 E). There is a zone between these two magmatic bodies where East-West trending mafic dykes of lamprophyric affinity intrude the Kaladongar Formation (Fig 2).

Gabbroic rocks of Kuran are dark coloured, mafic rich (mela gabbro). Pyroxene ($Wo_{44.82}En_{42.04}Fs_{13.14}$ and $Wo_{46.56}En_{40.95}Fs_{12.49}$) of euhedral to subhedral habit (41-49% volume), calcic plagioclase (22-33% volume) of andesine to labradoritic composition ($An_{37.1}$ to $An_{69.9}$) secondary oxy-hornblende and opaque minerals are the main minerals in gabbro (Fig.4a). Some pyroxene grains contain melt inclusions that crystallize into finer plagioclase crystals. The amphiboles (~6% volume) occur as rims around the pyroxenes. Accessory minerals, ilmenite and magnetite, also contain melt inclusions. Some opaque minerals show exsolution texture between ilmenite and magnetite. The texture is mostly intergranular and ophitic-subophitic. The mineral phases in the mafic dykes are oxyamphiboles (27-37% volume), plagioclase (Ab_{37-39}) (27-41% volume), clinopyroxene ($Wo_{48.26}$ $En_{37.94}Fs_{13.8}$ to $Wo_{49.09}En_{40.19}Fs_{10.72}$ (11-28% volume), opaque (3-7%) and secondary mineral such as chlorophaeite (Fig. 4b). The large (size few mm to 1-2 cm) oxyamphibole grains contain melt inclusion. The oxy-amphiboles are abundant and most of them are larger than the pyroxene grains. The larger grains are mostly euhedral having prismatic habit, comparatively less altered while finer grains are altered. The oxyamphibole grains are pleochroic from pale to dark brown. Some amphiboles have trapped carbonatitic and nephelinitic melt inclusions. The coastal alkaline dykes occurring south of Mumbai (Dessai, 1987, 1994; Dessai et al., 1990) include lamprophyric variety (camptonite). These are similar to the mafic dykes of the present study except that the former has less plagioclase in the groundmass.

The oxy-hornblende grains are highly pleochroic from dark brown to reddish brown and are of kaersutite composition having Al_2O_3=13.7-15.1 wt%, CaO=11.3-11.8 wt% and FeO of about 12.6-15.03 wt% in the dykes. The opaque minerals, mostly Fe-Ti oxide (ilmenite and magnetite) contains FeO_T (total Fe) from 61.85 to 93 wt% and TiO_2 in the range 2.2-33.8 wt%. Modal data and composition of the minerals in Kuran Gabbro and Kaladongar dyke are given in Das et al. (2007).

c) ***Rocks of Nir Wandh Complex:***

The Nir Wandh igneous complex with an exposed surface area of 3.5 sq. km is the largest intrusive body in Kutch. About 70-80% of the Nir Wandh pluton is made up of gabbroic mass with variable proportion of plagioclase and clinopyroxene. Other rock types are pyroxenite, foid-diorite and syenite/ nepheline syenite (Fig. 3). A dyke swarm of kaersutite bearing lamprophyre (camptonite) and fine-grained dolerite cross cuts across the complex. Some of these dykes can be discontinuously traced to Kaladongar anticline to the west (Fig. 2).

Pyroxenite is the basal member of the complex and consists of clinopyroxene, orthopyroxene and olivine with interstitial grains of plagioclase, clinopyroxene and opaque minerals (Fig. 4c). Larger grains show cumulus texture. Pyroxenite occurs as the basal member of the Nir Wandh complex.

Gabbro, the dominant member in the complex, consists of clinopyroxene (titan augite, z^ c=35°-40°), oxy-amphibole (kaersutite, z^c =15°-18°), plagioclase (symmetric extinction angle 30°-35°), olivine and opaque mineral (Fig. 4d). Pyroxene is often altered to kaersutite although primary kaersutite is also present. The rock shows ophitic, sub-ophitic and intergranular texture. Modal compositions of major constituent minerals are as follows- Titan augite 36 to 55%, plagioclase 28%. The gabbroic rocks can be classified as gabbro, pyroxene kaersutite gabbro and melagabbro (after Le Bas and Streckisen, 1991).

Foid-diorite has plagioclase, kaersutite, alkali feldspar, nepheline, apatite and opaque as the dominant minerals (Fig. 4e). Plagioclase is of labradorite composition and is frequently zoned. Kaersutite is pleochroic from pale brown to reddish brown with z^c varies between 16°-19°. Alkali feldspar and nepheline are present mostly as interstitial grains. Both nepheline and alkali feldspar occur as anhedral grains. Modal compositions of constituent mineral phases are as follows- plagioclase 31%, kaersutite 44%, titan augite- 3%, nepheline 11%, alkali feldspar 5%, opaque mineral 3.8% and apatite 2.2%.

Nepheline syenite occurs as small pockets in the gabbro. It is characterized by presence of alkali feldspar, nepheline, kaersutite, clinopyroxene, carbonate, apatite and opaque mineral. The rock is coarse grained with occasional phenocrysts of alkali feldspar and neheline. Nepheline is commonly euhedral. Clinopyroxene is pleochroic in shades of pink and marginally grades to green coloured aegirine augite. Both clinopyroxene and amphibole grains are subhedral. Modal compositions of constituent minerals are as follows- alkali feldspar 33%, nepheline 28%, plagioclase 22%, kaersutite 9%, clinopyroxene 2%, apatite 3%, opaque 1.7% and carbonate 1.3%.

Lamprophyre dykes are porphyritic with phenocrysts of clinopyroxene, kaersutite, olivine set in a groundmass of alkali feldspar, kaersutite, carbonate, orthopyroxene and ilmenite (Fig. 4f). The pyroxenes show simple twinning and zoning. The kaersutite phenocrysts are conspicuously zoned and contain entrapped melt inclusions. The pyroxenes range in composition from $Wo_{49}Fs_{25}En_{26}$ in the core to $Wo_{48}Fs_{9.5}En_{42.5}$ in the rim. Modal composition of constituent minerals are as follows- clinopyroxene 8.3 to 21.4%, kaersutite 7.7 to 24.7%, olivine 0.7 to 3.6%; in the groundmass clinopyroxene 1 to5.1%, kaersutite 3.5 to 14.5%, plagioclase 5.1 to 21.5%, alkali feldspar 4.4 to 5.6%, carbonate 2.1 to 7.3% and opaque 12 to 16%. In

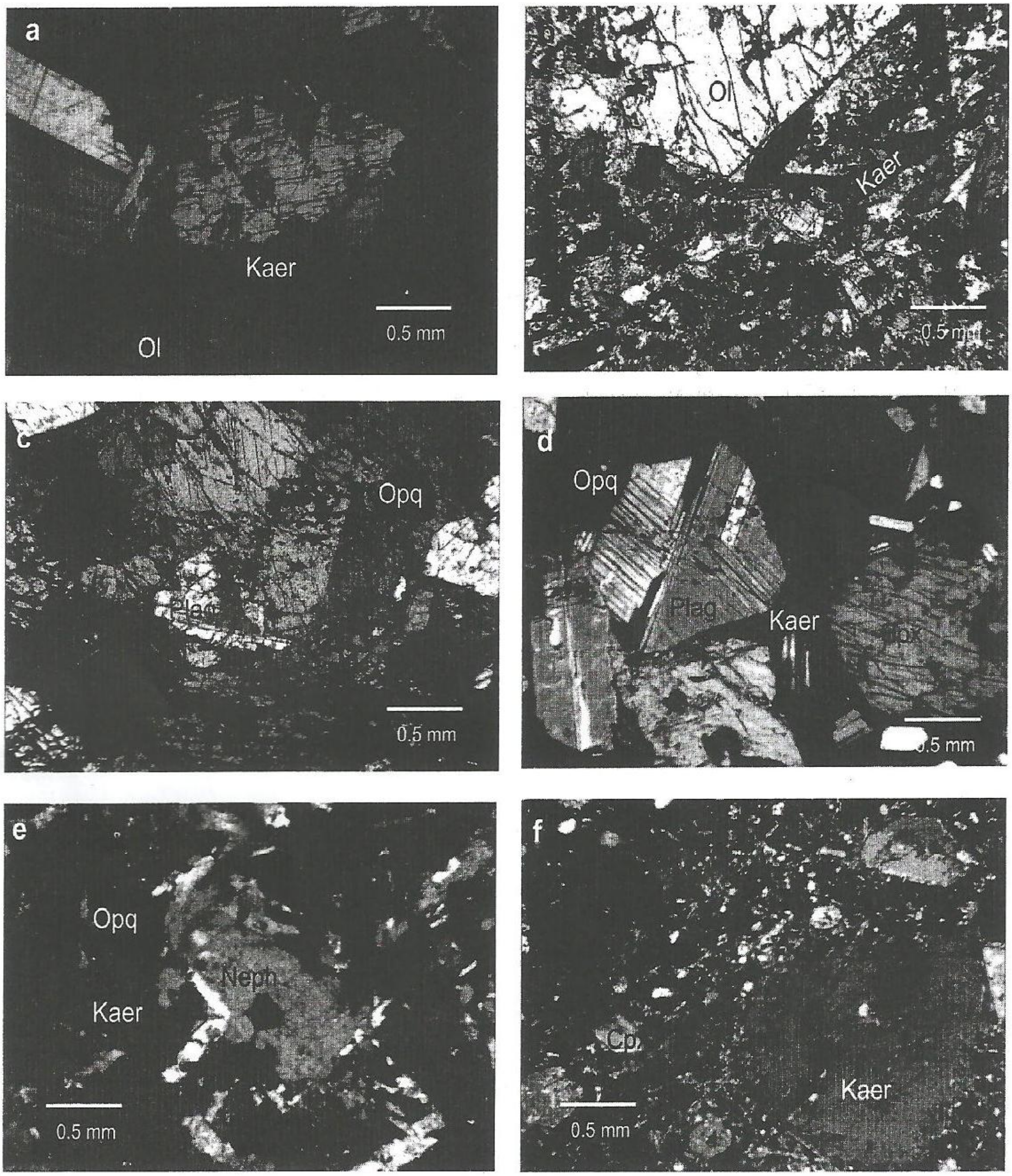

Fig. 4. Photomicrograph of Island magmatic rocks- (a) Kuran gabbro, (b) Kaladongar dyke, (c) Pyroxenite, Nir Wandh, (d) Gabbro, Nir Wandh, (e) Diorite, Nir Wandh, (f) Lamprophyre, Nir Wandh. Ol- olivine, Pl- plagioclase, Cpx- clinopyroxene, Opaq- opaque, Kaer- kaersutite.

contrast, the fine-grained mafic dykes (2-3 m wide) have kaersutite and plagioclase as the dominant minerals in a groundmass of plagioclase, kaersutite, clinopyroxene and opaque minerals.

All the rock types in Nir Wandh complex except pyroxenite have kaersutite. The kaersutite phenocrysts have MgO (10-11 wt%), TiO_2 (5.5 – 5.6 wt%) and total alkalis around 5 wt%. The groundmass kaersutite grains are Fe-rich (FeO, 24 – 30 wt%) with lower TiO_2 and MgO compared to the phenocrysts. Another significant aspect is that the composition of the phenocrystal kaersutite in the Nir Wandh complex is similar to that of the kaersutite phenocrysts of the mafic dykes of Kaladongar. Kaersutite phenocrysts of Nir Wandh Complex and Kaladongar mafic dyke contain carbonatitic and nephelinitic melt inclusions (our unpublished data).

GEOCHEMISTRY

Major and trace element abundances of magmatic rocks of Pachcham Island have been determined by XRF and ICPMS respectively at NGRI, Hyderabad. International standards like BHVO and JB-2 were also analysed along with the samples. Measured major and trace element abundances of the samples and the standards are given in Table 1 along with the recommended values of BHVO and JB-2 (Govindaraju, 1994). Detailed analytical procedure is given in Ray et al., (2006). Magmatic rocks of Pachcham Island can be grouped into two as follows:

Group 1- Sadara Sill, Kaladongar Dyke and Kuran Intrusive

Group 2- Nir Wandh Complex

In a TAS diagram (Fig.5) after Le Bas et al. (1986), the Sadara sill falls in the basalt field close to basalt-basanite boundary, the Kaladongar dykes, in the fields of basalt and tephrite-basanite and Kuran gabbro, in the picritic field. They have wide range of variation of total alkali but have a limited range of SiO_2. The samples fall in the field of picrobasalt, basalt, basaltic andesite, basaltic trachy-andesite, phono-tephrite and tephri-phonolite.

Major and trace element abundances of magmatic rocks of Pachcham Island is given in Table 1. Sadara sill samples have limited range of silica (45-47 wt% SiO_2), restricted range of total alkali (3.5-4.5 wt%), around 10 wt% MgO, 11 wt% CaO and 2 wt% TiO_2. Kuran gabbro is silica under saturated (around 43 wt% SiO_2) with moderately high MgO (8 wt%), high CaO (12-13 wt%), low alkali (around 2 wt%) and high TiO_2 (around 3.5 wt%). Kaladongar dyke, on the other hand, has variable silica (43.5-49.5 wt% SiO_2), high total alkali (5-7 wt%), moderately low MgO (4-6 wt%) and high TiO_2 (around 3 wt%). Nir Wandh rocks have limited range of silica (49-53 wt% SiO_2) but highly variable total alkali (1.3-10 wt%), Mg# (40-75) and TiO_2 (1-4 wt%).

In the Sadara sill, Kuran gabbro and Kaladongar dyke CaO and FeOt show positive correlation with MgO (Figs. 6a and 6b) while (Na_2O+K_2O) shows a negative correlation (Fig. 6c). Trace elements like La, Nb show negative correlation (Figs. 6d, 6e) and Ni is positively correlated with MgO (6f). On a primitive mantle normalized spidergram (Sun and McDonough, 1989) fields for Sadara sill, Kuran gabbro and Kaladongar dyke show similar pattern but with variable elemental abundances (Fig.7). The trace element abundances in Kuran gabbro is about 10 times abundant than that of the primitive mantle. Kaladongar dyke is most enriched in trace elements (around 100 times than mantle) while Sadara sill is intermediate between the two (around 50 times compared to the mantle). All of them show similar pattern with Sc, V and Y troughs. On a chondrite normalized REE diagram Kaladongar dykes show a LREE fractionated pattern (Fig. 8). Sadara sill samples also show a similar pattern. Kuran gabbro shows a relatively flat REE pattern without LREE enrichment.

In Nir Wandh Complex oxides like K_2O and Al_2O_3 are negatively correlated with MgO (Figs. 9a, 9b) while CaO is positively correlated with MgO (Fig.9c). Ni is negatively correlated with (La/

Table 1. Major and trace element abundances of magmatic rocks of Pachcham Island, Kutch basin, Gujarat.

	SADARA							KURAN			KALADONGAR MAFIC DYKE				
Sample	**P/3.1**	**P/3.2**	**P/3.3**	**P/3.4**	**P/3.5**	**P/3.6**	**P/3.7**	**P/1/01/03**	**P/2/01/03**	**P/3/01/03**	**BH28.2**	**BH32.1**	**BH32.2**	**BH32.3**	**BH33.1**
SiO_2	45.29	45.52	45.94	45.41	46.76	46.35	46.75	44.78	42.96	42.63	45.74	43.94	45.75	50.15	45.54
TiO_2	1.87	1.88	1.87	2.01	1.85	2.03	1.8	3.48	3.45	3.71	2.88	3.2	3.31	2.25	2.94
Al_2O_3	13.04	12.64	13.14	13.14	12.94	13.61	12.41	11.97	12.43	11.36	13.59	12.84	13.36	14.83	14.18
Fe_2O_3	12.02	11.8	11.61	12.17	11.44	11.7	11.69	14.11	14.74	17.16	13.88	13.55	12.63	11.3	13.95
MnO	0.16	0.17	0.17	0.17	0.16	0.17	0.16	0.15	0.15	0.19	0.15	0.17	0.16	0.18	0.17
MgO	9.23	10.72	9.87	10.11	9.67	9.01	9.66	7.89	7.94	8.31	8.5	6.47	6.42	4.31	6.26
CaO	11.57	12.15	11.91	11.93	12.04	11.76	11.13	12.84	13.05	12.76	8.22	11.85	10.8	7.69	8.39
Na_2O	2.74	2.99	3.05	3.1	2.98	3.13	2.54	1.9	1.87	1.98	3.45	3.29	3.16	4.32	4.04
K_2O	0.99	0.96	0.99	0.97	1.03	1.11	0.94	0.52	0.44	0.51	1.34	1.79	2.22	2.78	2.04
P_2O_5	0.52	0.51	0.58	0.52	0.57	0.62	0.53	0.2	0.21	0.18	0.83	0.97	0.93	0.87	1.01
Total	97.43	99.34	99.13	99.53	99.44	99.49	97.61	97.84	97.24	98.79	98.58	98.07	98.74	98.68	98.52
Mg#	0.64	0.68	0.66	0.66	0.66	0.64	0.66	0.57	0.56	0.53	0.59	0.49	0.54	0.47	0.51
Na_2O/K_2O	2.77	3.11	3.08	3.2	2.89	2.82	2.7	3.65	4.25	3.88	2.57	1.84	1.42	1.55	1.98
Ba	388.68	684.76	710.59	737.73	800.7	788.51	390.53	179.07	164.21	*	2077.58	1819.52	2048.96	2185.7	1674.78
Rb	16.04	15.12	15.91	15.39	16.58	18.65	15.34	10.9	11.39	*	25.1	39.06	49.88	89.54	51.19
Sr	546.24	667.41	712.12	710.52	803.18	761.66	528.51	357.35	335.44	*	1079.5	1416.22	1454.33	1434.66	1219.58
Y	24.84	24.21	25.05	24.75	25.2	26.46	24.38	18.28	18.2	*	28.09	31.79	30.42	32.4	31.17
Zr	178.26	164.22	173.9	170.33	172.27	185.96	174.49	88.71	89.09	*	236	288.38	282.52	438.23	347.54
Nb	45.42	42.97	46.38	46.59	45.05	51.36	44.34	15.8	16.22	*	69.77	101.95	100.57	135.88	102.56
Th	4.68	3.98	4.16	4.28	3.98	4.68	4.59	1.27	1.46	*	6.71	8.14	9.5	15.33	10.53
Pb	21.75	4.75	3.78	4.21	3.76	4.43	19.63	24.35	17.78	*	7.28	23	10.45	8.7	7.78
Ga	17.24	22.16	24.45	23.36	25.7	26.03	17.06	21.77	22.61	*	36.41	34.19	37.09	39.42	33.59
Zn	152.38	126.35	119.83	122.09	119.21	125.15	148.51	238.79	235.21	*	190.51	194.69	207.74	186.84	222.52
Cu	99.53	101.33	98.03	105.16	101.75	107.57	95.75	203.99	321.4	*	62.16	120.77	75.33	44.65	80.74
Ni	213.66	188.86	192.85	177.65	187.67	157.51	220.64	63.98	101.97	*	47.68	48.68	45.83	16.55	54.67
V	309.58	297.16	301.59	306.65	309.89	290.25	288.72	918.57	909.59	*	294.43	358.5	337.14	179.19	268.15
Cr	535.13	159.67	144.05	133.24	152.13	126.75	538.51	8.67	14.05	*	38.41	27.23	35.86	9.29	53.71
Hf	3.68	3.9	3.73	3.98	3.77	4.09	3.51	2.47	2.46	*	5.1	5.82	5.94	8.12	6.84
Cs	0.33	0.33	0.31	0.32	0.39	0.41	0.34	0.32	0.27	*	3.15	3.13	2.55	4.36	3.01
Sc	34.58	38.26	37	35.73	38.52	34.68	34.8	56.97	58.64	*	21.11	18.66	19.44	11.57	16.83
Ta	3.68	4.45	4.21	4.67	4.33	4.98	3.84	1.51	1.6	*	8.54	14.94	12.92	17.83	13.12
Co	76.95	72.46	73.74	74.65	80.79	66.37	73.72	92.61	92.08	*	48.98	58.43	55	31.38	52.25
U	0.67	0.74	0.76	0.77	0.74	0.86	0.66	0.2	0.24	*	1.19	2.02	1.64	2.89	1.98
La	32.13	33.84	34.37	36.22	33.07	38.08	31.48	10.59	10.94	*	45.49	62.7	65.04	83.45	67.55
Ce	64.82	67.36	68.08	72	65.47	75.42	63.6	24.54	24.76	*	90.9	125.39	125.73	153.74	131.27
Pr	6.25	6.46	6.53	6.91	6.25	7.15	6.09	2.71	2.72	*	8.75	12.07	11.95	13.6	12.23
Nd	34.65	33.39	33.08	35.54	32.33	36.72	33.92	16.61	16.7	*	44.37	60.14	59.67	63.34	60.04
Sm	6.14	6.52	6.5	6.83	6.39	7.02	5.77	3.7	3.62	*	8.35	10.79	10.4	10.32	10.25
Eu	2	2.15	2.11	2.21	2.08	2.26	2	1.42	1.35	*	3.16	3.73	3.7	3.58	3.56
Gd	6.86	6.87	6.71	7.13	6.62	7.36	6.69	4.4	4.22	*	9.29	11.87	11.69	11.54	11.42
Tb	0.93	0.98	0.96	1.01	0.95	1.03	0.92	0.65	0.65	*	1.24	1.52	1.45	1.43	1.45
Dy	4.44	4.63	4.6	4.87	4.52	4.92	4.43	3.46	3.19	*	5.49	6.43	6.26	6.17	6.22
Ho	0.84	0.87	0.86	0.91	0.85	0.92	0.85	0.63	0.64	*	1.01	1.13	1.1	1.14	1.11
Er	2.59	2.57	2.54	2.69	2.53	2.76	2.5	1.86	1.83	*	3.01	3.27	3.23	3.46	3.29
Tm	0.37	0.4	0.4	0.41	0.39	0.44	0.38	0.29	0.28	*	0.44	0.46	0.46	0.51	0.48
Yb	1.96	2.09	2.06	2.15	2.03	2.26	1.91	1.44	1.4	*	2.33	2.38	2.4	2.78	2.49
Lu	0.28	0.31	0.31	0.33	0.31	0.34	0.28	0.21	0.21	*	0.33	0.33	0.34	0.4	0.35
SREE	164.08	168.44	169.11	179.21	163.79	186.68	160.82	72.51	72.51	224.16	302.18	303.41	355.44	311.7	
(La/Yb)n	11.63	11.48	11.83	11.95	11.55	11.95	11.69	5.2	5.56	*	13.88	18.71	19.21	21.31	19.28

(Contd.)