Sindh Univ. Res. Jour. (Sci. Ser.) Vol.42 (2) 15-34 (2010)

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GEOCHEMISTRY, PETROGENESIS AND CRUSTAL CONTAMINATION OF HOTSPOT RELATED VOLCANISM ON THE NORTH WESTERN MARGIN OF INDIAN CONTINENT AND ITS IMPLICATIONS FOR PALEOSEDIMENTARY ENVIRONMENTS

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Received 12th March 2010 and Revised 07 October 2010)

Abstract

The Bibai volcanics of a proposed hotspot origin occur in the Suleman and Kirthar Ranges of Pakistan and are intermittently exposed near Waziristan, Zhob, Loralai, Muslim Bagh, Quetta, Khuzdar, Bela and Karachi areas in a zone more than 1200 km long and up to 2 km wide.

The volcanics are mainly alkali basalts but occasionally picro-basalt (MgO 17.57 wt %), trachybasalt, basanite, tephrite, hawaiite and trachyandesite are also found. Major and trace element chemistry confirm their alkaline affinity and within plate (hotspot) signatures. Major elements show enrichment in K_2O, TiO_2 and Al_2O_3 and depletion in CaO and MgO as compared to N-MORB. Their LILE and LREE enriched patterns and marked positive Nb and Ba anomalies are consistent with an enriched mantle source. The lower Mg # (41-61), REE, Zr - Zr/Y, La-Cr and Cr-Yb- study show that the parent magma for the Bibai volcanics was generated by 15%, partially melted garnet-lherzolite source and was fractionated in an upper level magma chamber. The source diagonastic ratios including K/Ba, P/Zr, and La/Ce for the Bibai and 0-2 Ma Reunion alkali basalts are almost similar, but the Bibai alkali basalts show higher K/Y, Sr/Y, Ba/Y and La/Yb ratios which indicate incorporation of crustal material into the Bibai parent magma. The Bibai alkali basalts also show remarkable enrichment in LILE and LREE relative to average 0-2 Ma Reunion and oceanic island alkali basalt, suggesting contamination of the parent magma by partial melts of Indian continental crust en-route to eruption.

Keywords: Geochemistry; petrogenesis; crustal contamination; hotspot related volcanics.

1. Introduction

The northwestern tectonic margin of the Indian continent and Afghan Block in Pakistan is marked by the Waziristan, Muslim Bagh and Bela ophiolite suture zone **(Fig. 1)**. These ophiolites and their associated melanges were sporadically emplaced onto the northwestern margin of the Indian continent during Late Cretaceous to Early Paleocene (Kojima *et al.,* 1994). The Bibai volcanic rocks are interstratified with the continental sediments of northwestern margin of the Indian plate, which occur in Suleman Range and found between Quetta and Muslim Bagh **(Fig. 1)**. Their close spatial location near the ophiolite compelled earlier workers to consider them to be a part of ophiolite sequence rather than having any entity of their own. The present paper mainly deals with geology, geochemistry, petrogenesis and crustal contaminations of Bibai volcanics and their implications on Paleosedimentary environments.

1.1 Previous Investigations

Several and diversified opinions have been presented by the past and present workers on the genesis and geotectonic setting of the Bibai volcanics. Vredenburg (1901) correlated the Bibai volcanics of Bela area with the continental tholeiites of Deccan trap. Jones (1960), DeJong and Subhani (1979) and Otsuki *et al.,* (1989) have considered these volcanics a product of Andean type volcanic arc, formed on the northwestern margin of Indian plate. Kazmi (1984), on the basis of field and petrological study, and Khan (1986) on the basis of petrological and geochemical data, suggested tholeiitic oceanic island arc environments for these volcanics. McCormick (1985) first recognized them as within plate alkali basalts on the basis of preliminary mineral chemistry of two samples and suggested that these volcanics were resulted by the motion of Indian plate over a hot spot as have already been proposed for the Ninety East Ridge **(Fig. 2)** of Indian Ocean by Sclator and Fischer (1974), and Chagos Laccadive Ridge (Mckenzie and Sclator, 1971). Sawada *et al.,* (1992) and Siddiqui *et al.,* (1994) on the bases of major and trace element geochemistry also favored the same idea. McCormick (1991) suggested that these volcanics are tholeiitic in nature and represent

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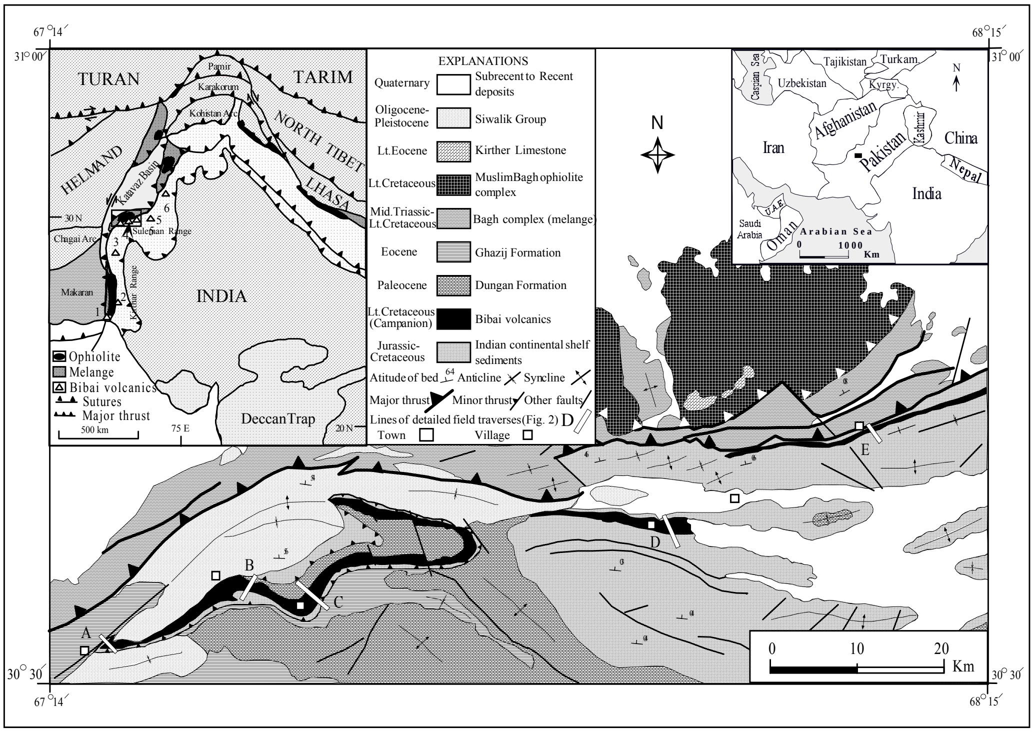

Fig. 1

Fig. 1 Geological map of Muslim Bagh area showing different localities of Bibai volcanics. The small inset map on upper right corner represent global setting, while larger inset map on upper left corner denotes regional geotectonic framework and different localities of Bibai volcanis in the area.

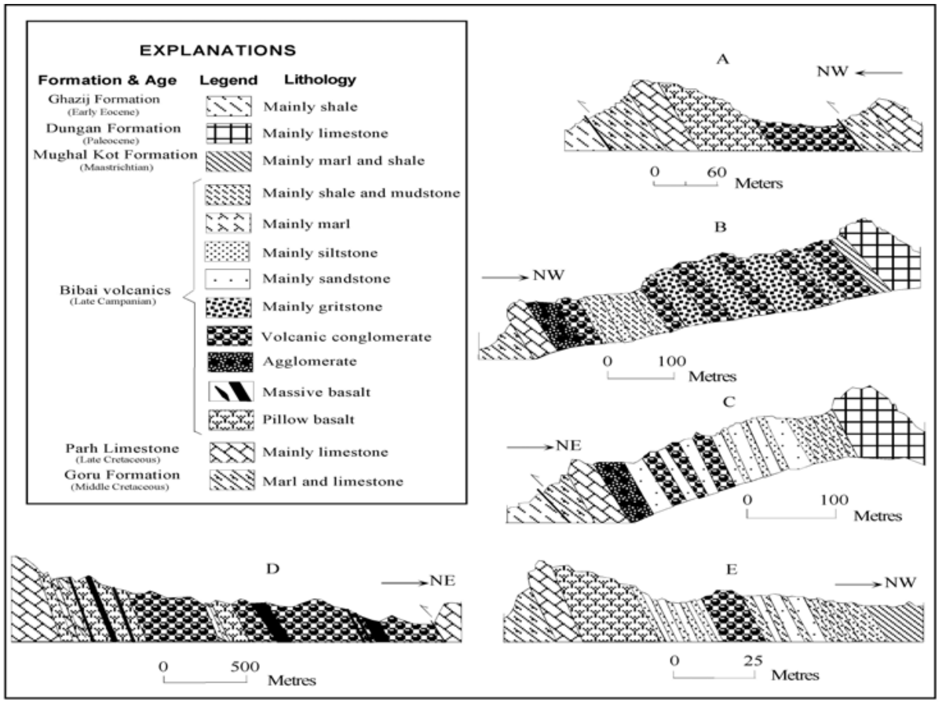

Fig. 2. Schematic geological cross sections exhibiting internal stratigraphy of Bibai volcanics and adjacent rock formations, in Saran Tangi, (A), Ahmadune (B), Kahan (C), Chinjan (D) and Gunda Manna areas (E).

the passage of Tethyan ocean floor over the Reunion hotspot and correlated these volcanics with Deccan tholeiites and Reunion lavas. He also suggested that this hotspot existed during Middle Triassic. He further suggested that these volcanics along with the Muslim Bagh ophiolite complex were tectonically emplaced onto the Pakistani continent in Paleocene time. McCormick (1991) has considered the Bibai volcanics exposed in Chinjan area **(Fig. 1)** and the within plate volcanics which occur in the melange zone of Muslim Bagh (Sawada *et al.,* 1992) and Bela Ophiolite Complex (Ahmed, 1991) as similar in origin. The latter studies showed that, although both the volcanics are similar in origin but were erupted in different ages and tectonic environments (Siddiqui et al. 1996 and Naka et al., 1996). The Bibai volcanics were erupted around 71 Ma on the northwestern margin of Indian continental plate and occur on top of the Late Cretaceous (Late Companion) Parh Limestone which is considered as a continental shelf limestone (Fatmi *et al.,*1986; Butt, 1986). The within plate alkaline and tholeiitic volcanics which are associated with Muslim Bagh and Bela Ophiolite Complex were erupted on the ocean floor of the Neo Tethys around 81 Ma and tectonically emplaced onto the north western margin of the Indian continental plate during 71 to 67 Ma (Sawada *et al.,*1995). Siddiqui *et al.,* (1996) on the basis of petrogenetic studies of Middle Triassic within-plate alkali basalts and its correlation with the 0-2 Ma Reunion alkali basalts; documented that Middle Triassic volcanics represent the first and earliest manifestation of mantle plume activity related with Reunion hotspot. Khan *et al.,* (1999) suggested that these volcanics represent the earliest magma generated from the rising Reunion hotspot plume.

2. Geology

Field aspects

The Bibai Volcanics are intermittently exposed near Zhob, Muslim Bagh, Quetta, Khuzdar and Bela areas. These volcanics are discontinuously exposed in an area more than 1200 km long and attaining a maximum thickness of about 2 km near Gurmai village south of Muslim Bagh (Fig. 1). The Bibai volcanics generally conformably overlie on top of the Parh Limestone of Late Cretaceous age (Hunting Survey Corporation, 1960) and are overlain by the Mughal Kot Formation of Maastrichtian age (William, 1959; Shah, 1999). Kazmi (1984) has given a Campanian age to the Bibai Volcanics on the basis of lower Campanian microfossils found in the lenticular bodies of limestone intercalated within the Lower part of the Volcanics. Siddiqui and Afzal (1999) on the basis of Late Campanian fauna (*Globotruncana calcarata*) assigned a Late Campanion age, whereas Sawada et al. (1995) have documented a 71.4 ± 3.4 Ma age on the basis of whole rock K/Ar radiometric age data. At places the Bibai Volcanics are unconformably overlain by the Paleocene Dungan Formation **(Fig. 2)** and the Pab Sandstone (H.S.C., 1960). Allemann (1979), DeJong and Subhani (1979) correlated the Poralai agglomerates, a part of Bela volcanics of (H.S.C. 1960) with Bibai volcanics. The subsurface basaltic rocks found during drilling, in the lower part of the Mughal Kot Formation near Karachi (Dubri Creek) are also included in the Bibai volcanics due to their similar stratigraphic position.

During the present investigations Bibai volcanic were studied in five different localities **(Figs. 1 and 2)** of Suleman range which include (A) Saran Tangi (N 30º 25' 15" and E 67º 13' 10"), (B) Ahmadune (N 30º 28' 29" and E 67º 23' 05"), (C) Kahan (N 30º 27' 28" and E 67º 27' 13"), (D) Chinjan (N 30º 31' 05" and E 67º 53' 32") and (E) Ghunda Mana area (N30º 37' 53" and E 68º 06' 15"). The Bibai volcanics are mainly represented by pillow and massive basaltic lava flow, agglomerate, volcanic conglomerate, tuffaceous sandstone, mudstone, shale and marl. The detailed internal stratigraphy of the above localities are illustrated in Fig. 2, and a brief description of each lithological unit is given below:

Pillow basalts: The amygdaloidal pillow basalts are well developed in Saran Tangi (Fig. 2 A), Chinjan (Fig. 2 D) and Ghunda Manna (Fig. 4 E) areas. In these areas pillow lavas occur on top of the micritic and sublithographic Parh Limestone and at places lenticular bodies or beds up to 50 cm thick, of the same limestone are also intercalated in the lower part of the pillow lava sequence, which contains Late Campanion fauna: *Globotruncana calcarata*. This pillow lava sequence is 80 m thick in Saranpangi, 525 m in Chinjan and 28 m in Ghunda Manna areas. The individual pillows in these areas range in diameter from 15 cm to up to 2 m. The pillows are generally without matrix in the lower part and gradually show arenaceous, sandy to silty matrix towards the upper part.

Massive Basaltic Lava Flows: Massive basaltic lava flows are found only in Chinjan area (Fig. 2 D), where three; lower middle and upper horizon occur intercalated with pillow lavas and volcanic conglomerates. In lower horizon three lava sheets are found intercalated with pillow lava flows, which are 3 to 35 metre thick. In the middle horizon massive lava flows are about 50 metre thick and occurs within the volcanic conglomerate. The upper horizon of massive lava flows are represented by three eruptions within the volcanic conglomerates. The lower two eruptions are 1.5 thick, while upper one is 70 metre thick. The massive lava flows in all three horizons are dark gay to black in colour and are amygdaloidal in nature.

Agglomerates: The agglomerates and tuffs are well developed in Ahmadune and Kahan areas **(Fig. 3** and **4 D and E)** and occur on top of the Parh Limestone. These are 5 to 20 meter thick and also contain 1 to 3 meter thick lenticular bodies of massive basalts. The agglomerates are mainly composed of lapillies and volcanic bombs 1cm to 1.5m in diameter, embedded in fine to medium grained volcanic ash.

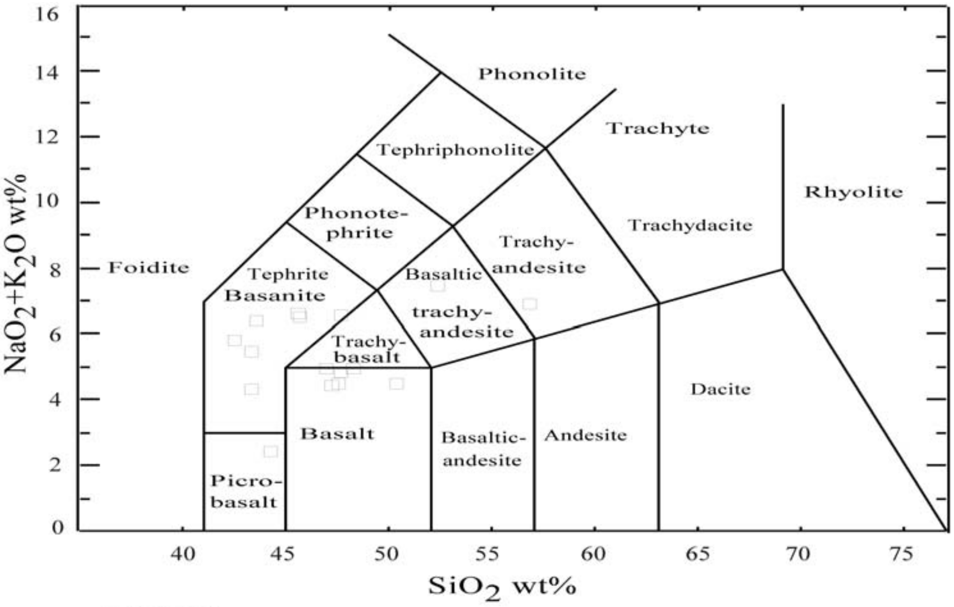

Fig. 3 Alkali versus SiO_2 plot for the Bibai volcanics (after Le Bas et al., 1986).

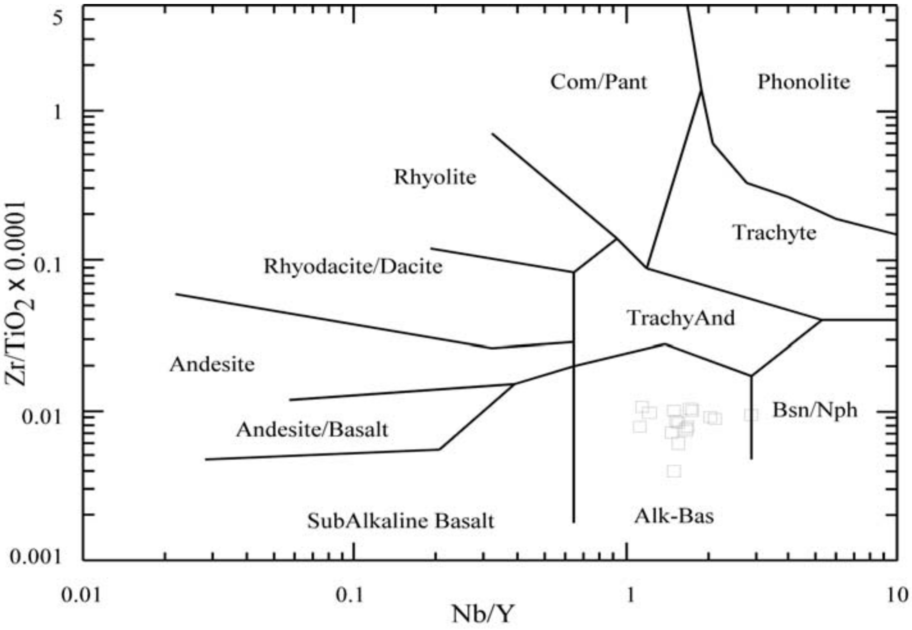

Fig. 4 Zr/ TiO_2 versus Nb/Y plot for the Bibai volcanics (after Winchester and Floyd, 1977).

Volcanic conglomerates: The volcanic conglomerates are observed in all the localities. The beds of volcanic conglomerates range in thickness from 20 to 50 meter. In Kahan and Ahmadune areas, the beds of volcanic conglomerates are intercalated with tuffaceous sanstones (Fig. 4 D and E). The volcanic conglomerates are mainly composed of rounded to subrounded fragments of various types of basalts (porphyritic, non-porphyritic and amygdaloidal), andesites, diorites, gabbros, limestone, sandstone, siltstone mudstone and radiolarian chert. These fragments range in diameter from less than 1 cm to 50 cm and are embedded in a tuffaceous sandy matrix.

Tuffaceous sandstone, mudstone, shale and marl: These rocks occur as intercalations in almost, all the localities (Fig. 4). The sandstone and siltstone are generally dominated in the lower part of Bibai volcanics whereas mudstone, shale and marl are dominated towards the upper part. The tuffaceous sandstone beds range in thickness from 15 centimeter to one meter. The tuffaceous siltstone beds range in thickness from 10 cm to 30 cm and tuffaceous mudstone beds from 2 cm to 15 cm and tuffaceous shale beds from 2.5 to 60 cm thick. The marl beds range in thickness from 30 cm to 3.5 meters.

3. Petrography

The Bibai volcanics exhibit porphyritic, cumulophyric, intersertal, pilotaxitic, trachytic and vitrophyric textures, cumulophyric to subcumulophyric textures being the most common. The main minerals are plagioclase (An_{36-88}), titaniferous augite diopside, olivine, phlogopite, lamprabolite (oxi-hornblende), nosean, sodalite, nepheline and devitrified volcanic glass **(Table 1)**. Apatite, ilmenite and magnetite occur as accessories. On the basis of petrographic studies, several varieties of basalts and other volcanic rock types are identified which include normal alkali basalt (R-1-10) (dominant), picro-basalt (MgO 17.57 wt %, R 11), trachybasalts (R 12), basanites (R 13 and 14), tephrite (R 15), hawaiites (R 16) and trachyandesites (R 17).

4. Geochemistry

Analytical Techniques: The major and trace elements were analyzed in the Geoscience Laboratory, Geological Survey of Pakistan, Islamabad, by X-ray fluorescence spectrometry (RIGAKU XRF- 3370E). The sample powder (<200 mesh) was thoroughly mixed with lithium tetra borate (flux) in a 1:5 sample to flux ratio and the glass beads thus obtained were analyzed by XRF. The REE, Th, Hf, and Ta were analyzed at the CHEMEX Laboratory Canada by INAA.

The analytical results and CIPW norms are presented in **(Table 2)**. The major elements are recalculated on a volatile free basis. All the volcanic rock suites presented in the Table 2 plot in their respective field in the SiO_2 versus alkali plot **(Fig. 3)**. In some instance non alkaline basalts also show high values for alkalies due to submarine alteration (Melson *et al.,* 1968; Fife, 1977). Therefore in order to confirm weather these rocks are truly alkaline or not, the samples are again plotted **(Fig. 4)** in Zr/TiO_2 versus Nb/Y diagram, which reveals that all the volcanic rocks are alkaline in nature

Major Elements: The major elements of Bibai alkali basalt show enrichment in K_2O, Na_2O, TiO_2, Al_2O_3 and P_2O_5 and depletion in CaO and MgO relative to N-MORB **(Tables 2 and 3)**, which are consistent with an alkaline series.

Incompatible Trace Elements: In incompatible elements in Bibai volcanic rocks are enriched in whole range of large ion lithophil elements (LILE) including Rb, Sr Th, U and Ba; and high field strength elements (HFSE) including Nb, Ta, Zr, Hf and Y relative to average N-MORB value (Sun and McDonough, 1989), which are consistent with basaltic alkaline rocks **(Tables 3 to 5)**. The Bibai volcanics has lower Zr//Nb and higher Ti/V and Zr/Y ratios (Table 2) than those of average MORB (Table 5), which are consistent of an enriched mantle source.

Spider Diagrams: The spider diagrams or multi-elements diagram are generally used to study the behavior of incompatible trace elements in the rocks and to constrain their source regions, with reference to N-MORB, primordial mantle or any other tectonically important compositions.

For this purpose samples from Bibai volcanics are plotted in N-MORB and primordial mantle normalized spider diagrams **(Figs. 5 A and B)** with normalizing values of Sun and McDonough (1989).

The incompatible trace element patterns in this diagram exhibit variable enrichment of whole range of trace elements including LIL and HFS relative to N-MORB and primordial mantle. These patterns also show relatively more enrichment of LILE relative to HFSE with distinct positive spikes on Ba, Nb and Zr that are consistent with an enriched mantle source (Pearce 1983; Wilson, 1989). In Oceanic Island Basalt (OIB) normalized spider diagram **(Fig. 5 C)** exhibited patterns of Bibai volcanic samples are almost parallel to normalized value of one suggesting a source identical to OIB, which are hotspot related volcanics.

Table 1. The salient petrographic features of the Bibai volcanics

Sam ple No.	*Rock Name*	*Locality (See Fig. 2)*	Occurrence	*Common Texture*	*Phenocrysts*	*Groundmass*	*Accessory Minerals*	*Secondary Minerals*
R 1-10	Alkali basalts	Saran Tangi Ahmadune Kahan & Chinjan	Pillow lava Massive basalt Volc. Conglo merate	cumulophyric to subcumul ophyric & subintersertal	ti-aug, pl(An_{36-88}), phl,	micro-cryptocrystalline & glassy, pl + ti-aug + phl + oxi-hbl + nosean	ap + il + mt	chl, ant, idd, chloroph celado, ura , chalced , cal , natro , stil, claymin
R 11	Picro- basalt	Chinjan	Dykes & Volcanic Conglom erates	porphyritic & subpilotaxatic	pl (An_{50-58}), diopol (Fo_{70-85})	microcrystalline pl + diop + ol+ diop	ap + mt +chr	ura , ant, idd
R 12	Trachybasalt	Ghunda Mana	Volcanic conglomerate	trachytic & pilotaxitic	ti-aug , aeg-aug , ne , ol	micro-cryptocrystalline pl + ti-aug + san + phl	ap + il + mt	chl , ant, clay min.
R 13,14	Basanite	Ghunda Mana	Pillow lava	Microcumuloph yric & subintersertal	ti-aug , phl	micro-cryptocrystalline & glassy , ti-aug + pl+ san + phl+ nosean+ ne	ap + il + mt	chl , chloroph , anti, cal, saus
R 15	Tephrite	Ghunda Mana	Pillow lava	Microcumuloph yric & subintersertal	ti-aug , phl	micro-cryptocrystalline & glassy, ti-aug + pl + san+ phl + nosean +ne	ap + il + mt	chl, chloroph, cal, saus
R 16	Hawaiite	Ghunda Mana	Pillow lava	microcumuloph yric	ti-aug	micro-cryptocrystalline & glassy, ti-aug + pl + san + nosean+ ne+ phl	ap + il + mt	chl, chloroph, celado, clay min, serp
R 17	Trachy–Andesite	Ahmadune	Volcanic conglomerate	trachytic	ti-aug , aeg-aug , ne , ol	micro-cryptocrystalline pl + ti-aug + san + phl	ap + il + mt	chl , clay min

Table 2. Bulk chemistry and CIPW norms of the Bibai volcanic rock suites.

Sample	R–1	R–2	R–3	R–4	R–5	R–6	R–7	R–8	R–9	R–10	R–11	R–12	R–13	R–14	R–15	R–16	R–17
SiO_2	47.55	47.97	48.63	47.92	47.25	50.70	45.85	47.98	45.97	50.74	44.66	52.73	42.90	43.61	43.68	43.91	57.21
TiO_2	2.41	2.17	2.31	2.29	2.34	2.45	2.98	2.96	2.97	2.49	1.59	2.77	3.88	2.99	3.76	3.69	1.90
Al_2O_3	16.21	15.44	15.67	15.60	16.22	16.79	17.98	15.93	18.08	16.75	10.61	16.36	14.82	14.43	15.39	14.86	15.87
Fe_2O_3	11.88	11.59	11.49	11.65	11.50	9.49	11.84	12.15	11.79	8.42	12.38	9.66	15.04	13.55	14.91	14.42	8.47
MnO	0.16	0.16	0.15	0.15	0.15	0.08	0.17	0.28	0.17	0.08	0.16	0.21	0.20	0.19	0.20	0.20	0.13
MgO	6.16	6.36	6.43	6.96	6.46	6.44	4.32	5.90	4.25	6.56	17.57	3.28	5.87	6.83	5.27	5.04	3.82
CaO	10.98	11.24	10.16	10.75	10.90	10.37	9.91	7.96	9.89	10.26	10.62	7.12	10.84	13.59	10.65	10.79	5.61
Na_2O	2.69	3.39	3.67	3.19	3.54	2.69	3.88	3.49	3.75	2.705	1.63	4.84	3.99	2.99	3.77	3.58	4.57
K_2O	1.55	1.29	1.12	1.13	1.22	1.61	2.52	2.87	2.56	1.59	0.59	2.44	1.66	1.15	1.50	2.61	2.13
P_2O_5	0.40	0.39	0.37	0.36	0.38	0.34	0.55	0.53	0.52	0.40	0.20	0.58	0.80	0.66	0.88	0.90	0.28
TOTAL	**99.99**	**100.00**	**100.00**	**100.00**	**99.9**	**99.96**	**100.00**	**100.05**	**99.95**	**99.99**	**100.01**	**99.99**	**100.00**	**99.99**	**100.01**	**100.00**	**99.99**
Mg #	52	52	53	54	53	57	42	49	42	61	74	40	44	50	41	41	47
V	352.0	290.0	297.0	325.0	312.0	318.0	314.0	322	309.0	334.0	279.0	233.0	376.0	410.0	347.0	347.0	200.0
Cr	93.0	206.0	145.0	178.0	121.0	170.0	107.0	101.0	93.0	175.0	153.0	52.0	36.0	119.0	41.0	31.0	139.0
Co	46.0	50.0	55.0	55.0	59.0	38.0	51.0	69.0	51.0	35.0	115.0	42.0	85.0	54.0	78.0	70.0	39.0
Ni	74.0	109.0	101.0	107.0	89.0	93.0	67.0	83.0	48.0	103.0	732.0	12.0	30.0	95.0	29.0	23.0	40.0
Cu	97.0	165.0	119.0	104.0	97.0	92.0	38.0	62.0	41.0	97.0	103.0	17.0	38.0	191.0	35.0	40.0	34.0
Zn	107.0	97.0	99.0	96.0	98.0	107.0	102.0	108.0	106.0	99.0	87.0	103.0	155.0	119.0	163.0	156.0	80.0
Y	26.0	25.0	23.0	24.0	24.0	32.0	27.0	33.0	30.0	35.0	16.0	34.0	40.0	27.0	42.0	42.0	25.0
Zr	158.0	199.0	83.0	126.0	181.0	217.0	235.0	204.0	248.0	236.0	105.0	210.0	346.0	258.0	264.0	343.0	134.0
Nb	41.0	40.0	37.0	40.0	39.0	41.0	61.0	58.0	65.0	43.0	28.0	57.0	75.0	84.0	75.0	77.0	30.0
Rb	31.0	28.0	20.0	31.0	24.0	33.0	51.0	61.0	56.0	37.0	17.0	41.0	36.0	18.0	48.0	47.0	38.0
Sr	158.7	616.0	2048	1729.0	77.0	560.0	736.0	627.0	765.0	583.0	492.0	1223.0	454.0	1128.0	1635.0	594.0	438.0
Ba	611.0	472.0	913.0	491.0	425.0	617.0	770.0	591.0	741.0	528.0	276.0	1910.0	573.0	836.0	589.0	842.0	385.0
Zr/Nb	3.85	4.98	2.24	3.15	4.64	5.29	3.85	3.52	3.82	5.76	3.75	3.68	4.61	3.07	3.52	4.45	4.47
Zr/Y	6.07	7.96	3.61	5.25	7.54	6.78	8.70	6.18	8.26	6.74	6.56	6.18	8.65	9.56	6.29	5.79	5.36
Ti/V	41.08	44.90	46.66	42.26	45.0	46.23	56.94	55.16	57.67	44.43	34.19	71.33	61.91	43.76	65.01	63.80	57
Ti/Zr	91.52	65.43	166.51	109.05	77.57	67.74	136.64	87.06	71.85	142.29	90.86	79.14	90.23	69.53	85.45	64.55	85.07
Qz	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Or	9.21	7.66	6.69	6.76	6.53	6.87	14.57	14.99	15.58	17.07	3.54	9.87	8.94	18.14	15.58	15.25	23.74
Ab	23.01	23.03	28.71	25.45	0.39	8.55	41.21	15.94	10.59	24.31	10.93	14.01	17.54	18.75	10.59	16.42	21.12
An	27.82	23.31	23.13	25.12	22.33	22.73	15.72	24.37	16.92	19.43	20.08	19.17	20.84	17.23	16.92	25.10	17.32
Ne	0.00	3.18	1.41	0.94	14.45	9.21	—	9.30	10.81	2.95	1.60	10.77	7.93	14.36	10.81	8.43	15.18
Di	19.76	24.48	20.26	21.11	20.10	32.94	12.60	17.23	25.10	13.47	25.29	22.94	20.15	13.60	25.10	16.59	10.44
Hy	0.51	—	—	—	—	—	1.94	—	—	—	—	—	—	—	—	—	—
Ol	8.38	7.87	8.89	9.84	28.30	5.82	1.05	4.56	4.13	9.16	30.52	6.69	6.17	4.39	4.13	4.63	3.58
Mt	5.76	5.41	5.63	5.58	4.26	6.60	6.26	6.60	7.68	6.60	4.53	7.73	7.79	6.32	7.68	6.60	4.51
He	4.62	4.17	4.42	4.38	2.86	5.73	5.29	5.70	7.07	5.66	3.04	6.97	7.21	5.30	7.07	5.69	2.90
Ap	0.92	0.90	0.86	0.83	0.79	1.54	1.35	1.29	2.11	1.23	0.47	1.86	2.07	1.91	2.11	1.29	1.20

Table 3. A comparison of major and trace elements of average MORB, Bibai, Hawaii, Ascension and Tristan Da Cunha Alkali basalts.

	N-MORB 1	*E-MORB 2*	*BIBAI*	*HAWAII (Hualalai) 3*	*ASCENSION 4*	*TRISTAN-DA CUNHA 5*
Major element Wt %)						
SiO_2	50.40	51.18	48.06	46.37	46.40	40.36
TiO_2	1.36	1.69	2.54	2.40	3.47	3.54
Al_2O_3	15.19	16.01	16.47	14.18	15.58	16.19
Fe_2O_3	10.01	9.40	11.08	14.99	14.04	11.37
MnO	0.18	0.16	0.16	0.19	0.22	0.18
MgO	8.96	6.90	5.98	9.47	5.22	4.57
CaO	11.43	11.49	10.25	10.33	9.20	9.45
Na_2O	2.30	2.74	3.30	2.85	3.53	3.97
K_2O	0.09	0.43	1.75	0.93	1.24	3.15
P_2O_5	0.14	0.15	0.42	0.28	0.95	1.42
Trace elements (PPM)						
Nb	2	8.6	47	16	46	110
Zr	97	121	189	160	225	300
Y	37	39	28	21	38.8	50
Rb	2.3	10	37	22	20	40
Sr	98	155	1003	500	426	1400
Ba	20	97	616	300	280	1000

NOTE: Values in columns 1 and 2 after Humphris et al 1985, 3- after Schilling et al 1984, 4-after Weaver et al 1987 and 5-after Baker et al 1964.

Table 4. Rare earth and trace elements comparison of alkali basalts of the Bibai volcanics, with average Hawaii, MORB, OIB and Reunion hotspot alkali basalts.

	SR-1	SR-2	SR-3	SR-4	SR-5	SR-6	Ave. Bibai Volcanics	Hawaii (Hualalai) 1	N–MORB 2	E-MORB 3	Ave. OIB 4	Reunion Hotspot 5
La	47	49	46	36	86	57	53.5	—	2.5	6.3	37	22.77
Ce	106	116	102	82	172	142	120	43	7.5	15	80	54.38
Nd	40	35	35	35	40.0	50	39.16	—	7.3	9	38.5	29.15
Sm	10.30	11.30	9.70	8.40	10.20	10.30	10.03	5.35	2.26	2.6	10	6.65
Eu	3	3.5	3.0	2.50	3.0	2.50	2.92	1.76	1.02	0.91	3	2.13
Tb	3	0.80	1.40	0.90	0.70	1.20	1.3	—	—	—	—	-
Yb	2	2.10	1.80	1.90	2.40	2.1	2.05	1.88	3.05	2.37	2.16	1.99
Lu	0.30	0.30	0.30	0.30	0.40	0.30	0.32	—	0.45	0.35	0.3	—
∑REE	208.6	217.2	197.8	166.1	314	264.2	227.98	—	24.08	36.53	170.96	—
Ta	4	4	4	2	12	4.0	5.0	—	0.132	0.47	2.7	—
Th	7	6	6	5	13	6.0	7.16	1.2	0.12	0.60	4	3.67
Hf	8	8	8	8	8	8.0	8.0	3	2.05	2.03	7.8	—
U	1	2	2	1	4	1	1.83	—	0.047	0.18	1.02	—
Hf / Ta	2.0	2.0	2.0	4.0	0.67	2.0	1.6	—	—	—	2.88	—
La / Ce	0.44	0.42	0.45	0.43	0.5	0.40	0.45	0.44	0.33	0.42	0.46	0.44
La / Yb	23.50	23.33	25.56	18.95	35.83	27.14	26.1	10	0.52	2.66	17.12	11.44
Th / Yb	3.50	2.86	3.33	2.63	5.42	2.86	3.49	6.38	0.04	0.25	1.85	1.84
La_N/Yb_N	15.71	15.60	17.09	12.67	23.96	18.15	17.45	—	0.55	1.78	11.45	7.65
Ce_N/Yb_N	13.48	14.05	14.41	10.98	18.23	17.20	14.89	—	0.63	1.61	9.42	6.95
La_N/Sm_N	2.82	2.68	2.93	2.64	5.20	3.41	3.29	—	0.68	1.50	2.28	2.11
La_N/Ce_N	1.17	1.17	1.19	1.15	1.31	1.06	1.17	—	0.88	1.10	1.22	1.10

NOTE: The values in SR-1 to SR-6 are after Siddiqui et al., 1996, the values in column No. 1 is after Schilling et al., 1985, 2, 3 and 4 are after Frey & Clague et al., 1983 and 6 after Fisk et al., 1988.

Table 5. Comparison of trace elements and their ratios of average MORB, average alkali basalts from Oceanic island, Bibai, Hawaii, Tristan Da Cunha, Ascension and Reunion hotspots.

	N–MORB 1	E–MORB 2	BIBAI	OIB 3	HAWAII (Hualalai) 4	TRISTAN-DACUNHA 5	ASCENSION 6	REUNION HOTSOPT 7
Rb	0.56	5.04	37.0	31.00	22.00	40.00	20.00	19
Ba	6.3	57.00	616.0	350.00	300.00	1000.00	280.00	210
K	598.0	2092.0	14525.0	11952.0	7719.00	26145.0	10292.0	7636
Nb	2.33	8.30	47.00	48.00	16.00	110.00	46.00	25
Sr	90.0	155.0	1003.00	660.00	500.00	1400.0	4216.0	429
Zr	74.0	73.0	189.00	280.0	160.00	300.00	225.00	209
Ti	7614.0	6012.0	15240	17232.0	14400.0	21240.0	20082.0	16680
Y	28.00	22.00	28.0	29.00	21.00	50.00	38.00	29
Th	0.12	0.60	7.16	2.7	1.20	—	—	3.67
Hf	2.05	2.03	8.00	7.8	3.00	—	—	-
Ta	0.132	0.47	5.00	2.7	—	—	—	-
P	616	660	1848	2728	1232	—	—	1584
Zr / Nb	31.75	8.80	5.83	4.02	10.00	2.73	4.89	8.36
Zr / Y	2.64	3.17	9.66	6.75	7.62	6.00	5.92	7.21
P / Zr	8.32	9.04	9.79	9.74	7.70	—	—	7.58
K / Ba	94.92	37.0	25.00	28.00	25.70	26.14	36.75	36.36
Ba /Nb	2.7	6.9.0	13.00	7.30	18.75	9.09	6.08	8.4
Ti / Zr	102.89	82.36.0	80.00	61.54	90.00	70.8	89.25	79.81
K / Rb	1067.0	415.0	410.00	386.00	350.00	653.62	514.6	401.89
Sr / Y	3.20	7.04	35.82	22.76	23.81	28.00	110.00	14.79
K / Y	21.35	95.10	519	412	368	—	—	263.31
Ba / Y	0.23	2.59	22.00	14.29	12.07	20.00	7.37	7.24
Ti / Ba	1209	105	24.74	49.23	48.00	21.24	71.72	79.43

NOTE: Values in cloumns 1,2 and 3 after Frey and Clague, 1983, 4 after Schilling *et al..,*1984,5 Baker *et al..,*1964, 6 after Weaver et al., 1987 and 7 after Fisk *et al..,* 1988.

Compatible trace Elements: In compatible elements these rocks are generally low in Cr (31-206 ppm), Ni (12-109 ppm) and Co(35-85 ppm) except in one sample of picro-basalt (R-11) in which Ni and Co values are higher (732, and 115 ppm respectively)

Rare Earth Elements (REE): The rare earth elements (La, Ce, Nd, Sm, Eu, Yb and Lu) are analyzed for six samples (Table 3). The whole range of REE are enriched relative to average N-MORB value (Sun and McDonough, 1989) and have higher value total REE (∑ REE) than those of the average values of N-MORB, E-MORB and OIB. The Bibai volcanics also have higher values of normalized LREE/HREE ratios (La_N/Yb_N = 12.71-23.96, Ce_N/Yb_N = 10.98-18.23) as compared to average N-MORB value (La_N/Yb_N= .55, Ce_N/Yb_N = 0.63), which are evident for their derivation from an enriched mantle source.

Chondrite Normalized REE Diagrams: Chondrite normalized REE diagrams are generally prepared to determine the behavior of REE in the rocks and to constrain their source compositions, with reference to normalized chondritic values. The Chondrite normalized REE diagrams **(Fig. 5)** of Bibai volcanics (Nakamura, 1974) shows variable LREE enriched patterns, which are consistent with the enriched mantle source and indicate the presence of residual garnet in the parent magma source (Clague and Frey, 1982).

5. Petrogenesis

Nature of Parent Magma: The petrological and petrochemical studies of Bibai volcanics (Tables 1 and 2) show that these rocks are quartz free and contain modal and normative olivine, nepheline and alkali feldspar. Therefore, according to the classification of Yoder and Tilly (1962), Carmichael *et al,.* (1974), and TAS classification of IUGS (Le Maitre *et al.,* 1989), all the rock suites of Bibai volcanics belong to alkali basalt series. The SiO_2 versus alkali plot (Fig. 8 A) confirm their alkaline nature and suggests that they belong to mildly alkaline series. The ternary plot of normative

An-Ab-Or shows that these are Na-rich alkali basalts (Fig. 7 B). The Bibai volcanics of the Bela area (Fig. 1) have already been proved to be within plate alkali basalts (Sarwar, 1981) Their Zr/Nb, Zr/Y, Ti/V and Ti/Zr ratios (Table 2) are also consistent with the documented ratios (Pearce and Norry, 1979 ; Shervais, 1982 ; Pearce, 1983) for alkali basalts.

The criteria generally used to determine whether the basalts occurring in an area represent the primary melts from the mantle peridotite source or these are the product of fractionated liquids, is as follows:-

a) The presence of mantle peridotite (lherzolite) xenoliths within the basaltic volcanics series.

b) The high MgO contents and higher magnesium number (Mg # = Mg/Mg+Fe^{2+}).

c) Higher contents of compatible elements (Ni, Cr and Co).

The basaltic magma coming from up to 30% partially melted mantle peridotite source must have Mg # in the range of 68-75 (Green, 1976; Frey *et al.,* 1978; Hanson and Langmuir 1978). Gill (1981) has suggested a Mg # $\geq$ 67, whereas Tatsumi and Eggins (1995) have documented a Mg # > 70 for primary basaltic magmas. The basalts with 250-300 ppm Ni and 500-600 ppm Cr contents are considered to be derived from a primary mantle source (Perfit *et al.,* 1980; Wilkinson and Le Maitre, 1987). The Co contents in primary basaltic magma must range from 27-80 ppm (Frey *et al.,* 1978).

So far no mantle lherzolite xenolith is reported from any Bibai volcanic rock assemblage in Pakistan. The MgO (3.82-6.96 wt %) Mg # (40-61), Ni (12-109 ppm), Cr (21-206 ppm) and Co (26-41 ppm) contents in most of the basaltic rocks of Bibai volcanics are well below the values just mentioned (Table 2), except in the case of one picro-basalt sample which is taken from the chilled margin of a porphyritic gabbro dyke transecting the pillow lavas and volcanic conglomerate. The MgO contents and Mg # are 17.57 wt. % and 74 respectively. The Ni, Cr and Co contents in these rocks generally range from 12-109 ppm, 31-206 ppm and 35-78 ppm, respectively. In picro-basalt sample Ni, Cr and Co contents are 732 ppm, 153 ppm, and 115 ppm. It is therefore suggested only picro-basalt may represent the partial melts from an enriched mantle peridotite source or alternatively it may represent the earliest fractionated liquid formed due to the cumulus enrichment in the lower magma chamber. Rest of the rock assemblege have not directly derived from the primary melts from the deep mantle reservior, but were fractionated in an upper level magma chamber.

Nature of the Source of Parent Magma: The Zr versus Zr/Y and Cr versus Y diagrams **(Figs.5, 6 and 7)** provide useful information about the nature of source, degree of partial melting and fractionation etc. The plot various samples of Bibai volcanics in this diagram suggest that the parent magma was generated by 10-15% partially melted enriched source. The 0-2 Ma Reunion hotspot alkali basalts (Fisk *et al.,* 1988) also plot **(Fig. 6A)** in the same field, suggesting the similar degree of partially melted enriched mantle source for the parent magma and similar degree of fractionation for both the volcanic groups.

A comparison of average major and trace elements of N-MORB and alkali basalts from Bibai, Reunion, Hawaii (Hualalai), Ascension and Tristen Da Cunha (Table 4 and 5) show resemblance of average bulk chemistry of Bibai volcanics with other hotspot related volcanics.

6. Tectonic Setting

A number of plots and tectonomagmatic discrimination diagrams based on major, minor or trace elements are designed to study the parent magma and tectonic setting of the volcanic rocks. The diagrams based on major elements or large ion lithophile (LIL) elements must be used with great caution, as these elements are more mobile during post-magmatic alteration or metamorphic processes as compared to high field strength (HFS) elements (Pearce and Can; 1973; Winchister and Floyed, 1977).

The plots of samples from Bibai volcanics in various discrimination diagrams, including, TiO_2-MnO-P_2O_5 plot (Mullen, 1983), suggest that they belong to oceanic island arc alkali basalts. The Ti-Zr-Y **(Fig. 8 C)**, and Zr versus Zr/Y plots **(Figs. 8 D and E)** propose their within plate origin, while Nb-Zr-Y plot **(Fig. 8 F)** further confirm their within plate alkaline signatures.

7. Crustal Contamination

The crustal contamination studies of within plate basalts offer great difficulties owing to their source heterogeneities caused due to the difference in the degree of partial melting and the depth of enriched mantle sources. The Zr versus Zr/Y studies (Fig. 6) and the average La/Ce, P/Zr and K/Ba. (Tables 4 and 5) ratios which are diagnostic for source composition (Wilson, 1989) are more or less similar for Bibai and 0-2 Ma Reuniion alkali basalts,

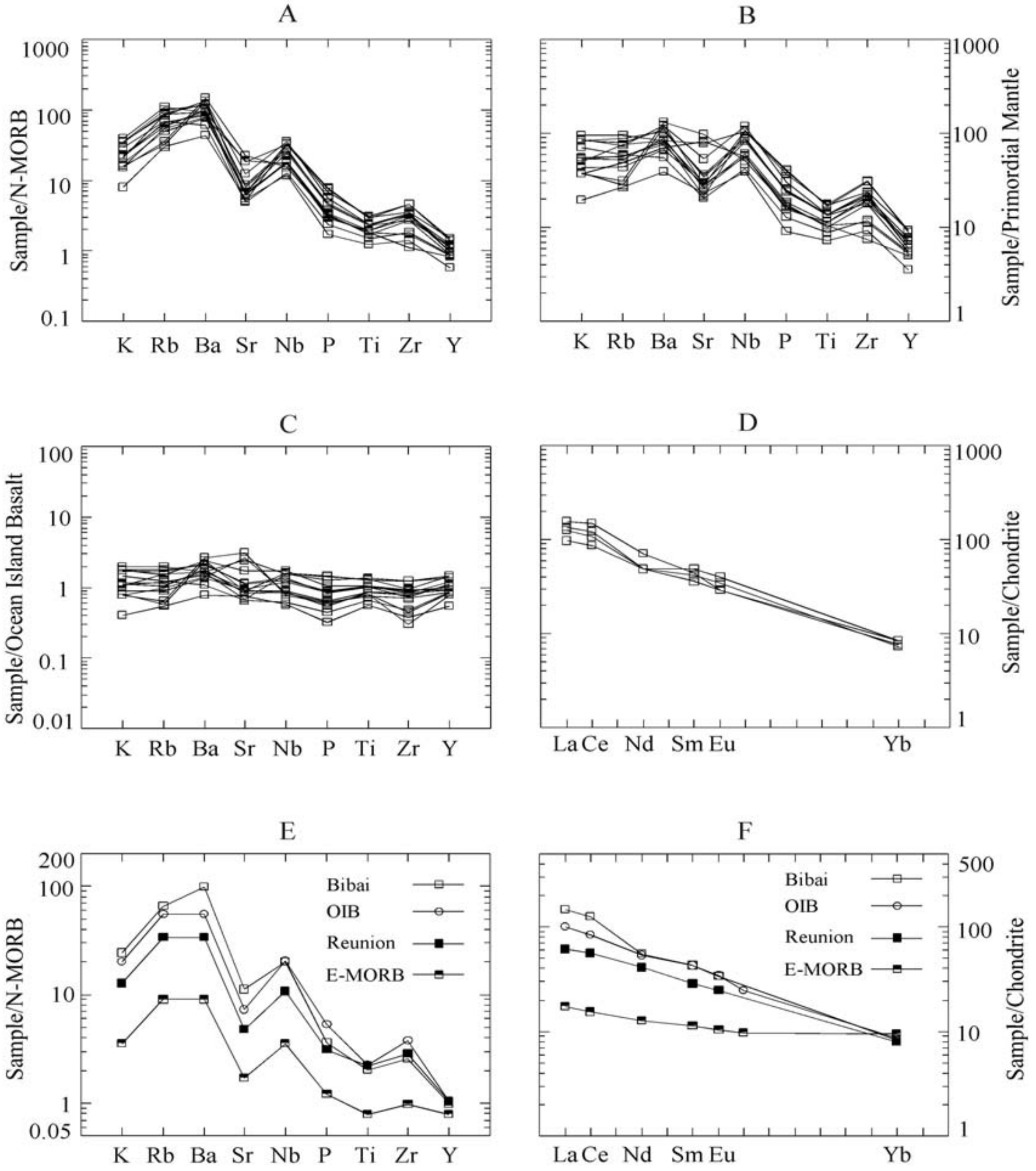

Fig. 5 (A) N-MORB, (B) Primordial mantle, (C) Oceanic Island Basalt (OIB) normalized spider patterns and (D) Chondrite normalized REE diagram for the volcanic rock suites from the Bibai volcanics with N-MORB normalized diagram for average Bibai, OIB, Reunion and E-MORB (E) and Chondrite normalized REE diagram for average Bibai, OIB, Reunion and E-MORB (the normalization values for spider patterns are after Sun and McDonough, 1989 and for Chondrite normalized REE diagram are after Nakamura, 1974).

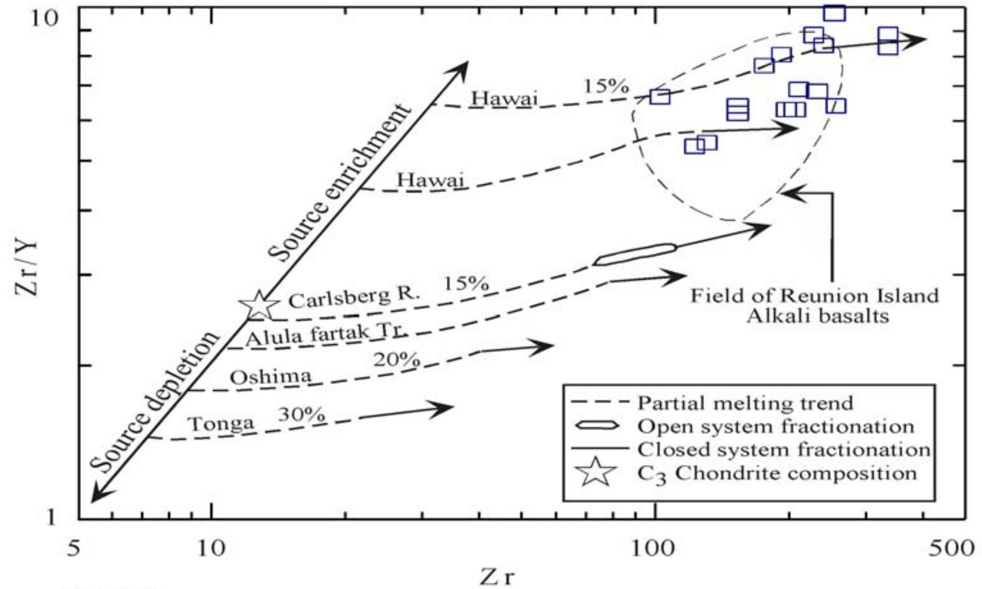

Figure 6.

Fig. 6 (A) Zr versus Zr/Y plot for the various rock suites from the Bibai volcanics (after Pearce and Norry, 1979).

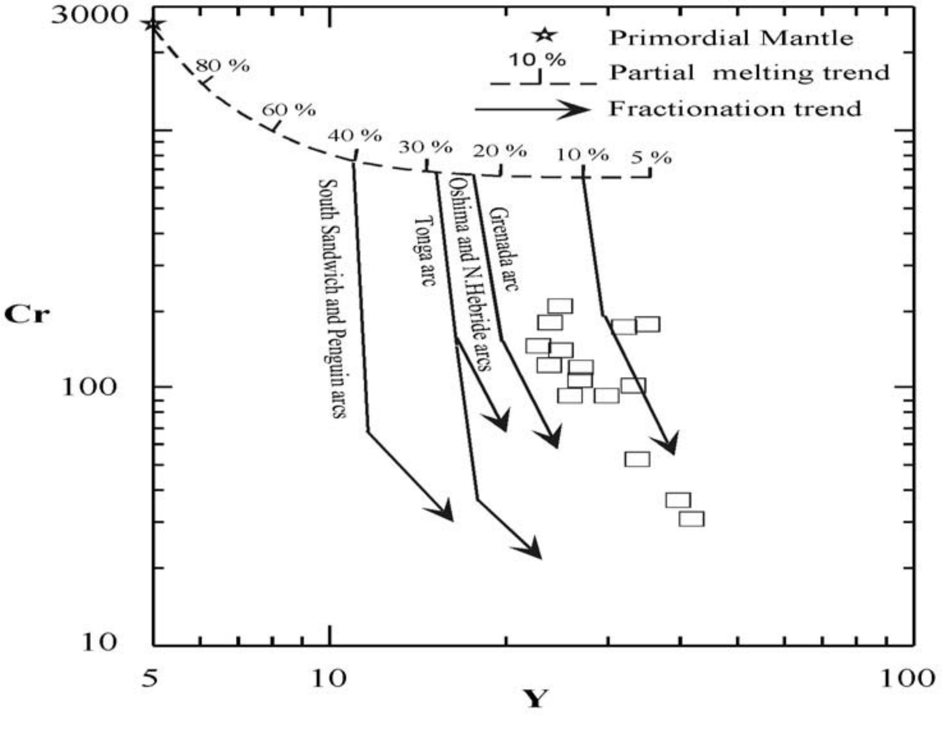

Fig. 7 Cr versus Y plots for the various rock suites from the Bibai volcanics (after Pearce and Norry, 1979).

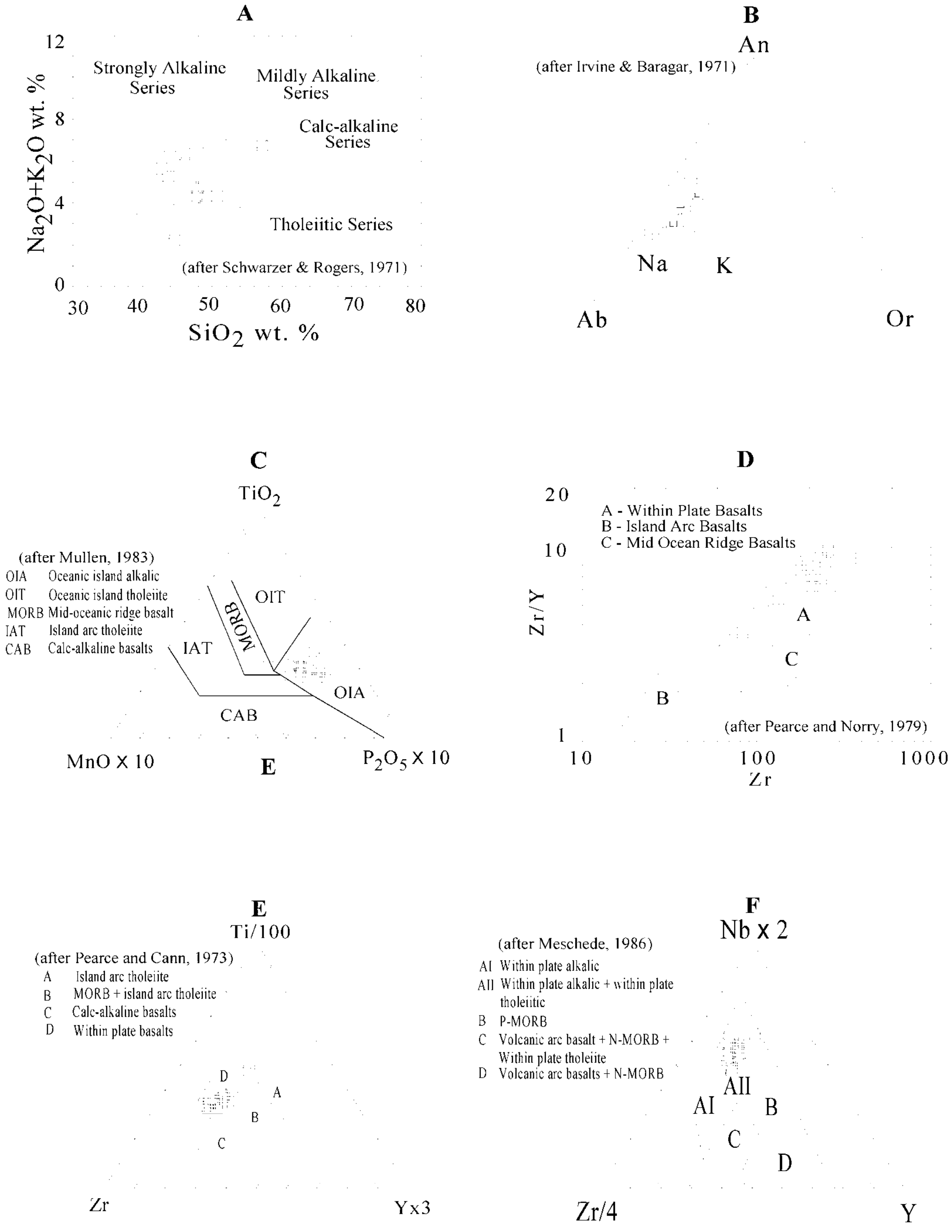

Fig. 8 (A) Alkali versus SiO_2, (B) ternary plot of normative An-Ab-Or, (C) TiO_2 MnO-P_2O_5 ternary plot, (D) Z versus Zr/Y diagram, (E) Ti-Zr-Y and (F) Nb-Zr-Y tectonomagmatic discrimination diagrams for the Bibai volcanics.

revealing similar enriched mantle sources. The Bibai volcanics have higher La/Yb, K/Y, Sr/Y, Ba/Y, K/Rb, and lower Zr/Nb, Ti/Ba, Ba/Nb, Ti/Zr ratios, which suggest the contamination of the parent magma of the Bibai volcanics with the continental crustal melts before eruption. The MORB and chondrite normalized REE trace element patterns of average Bibai, 0-2 Ma Reunion alkali basalts and average OIB (Figs. 5 E and 5 F) exhibit more LILE and LREE enrichment for the former indicating the crustal contamination. Most of above mentioned ratios and remarkable increase in Th, Ba, Rb, Sr and K in the average Bibai volcanics relative to average oceanic island basalt (OIB) and 0-2 Ma reunion alkali basalts are also in broad agreements with crustal contamination of the parent magma. For further confirmation, the samples of Bibai volcanics are plotted in some famous discrimination diagrams generally used for this purpose.

The plot of the Bibai volcanics in TiO_2-K_2O-P_2O_5 diagram exhibits a progressively increasing trend parallel to the mixing vector projecting towards K_2O apex **(Fig. 9 A)**. The ternary plots of Zr/Nb-Y/Nb-Rb/Y and Zr/Nb-Zr/Y-Ba/Y ratios for the Bibai volcanics show a progressively increasing trend towards Rb/Y and Ba/Y apexes in Figures 9 B and C respectively. The Rb/Y and Ba/Y ratios are generally distinctly higher in continental crustal rocks. The plots of the Bibai volcanics in these ternary diagrams confirm the variable incorporation of crustal material into the Bibai primary magma before its eruption through Indian continental crust.

8. Discussion

The petrogenetic study in the foregoing pages strongly suggests that the Bibai volcanics are hotspot related alkali basalts which represent the Late Cretaceous (71.4 ± 3.4 Ma) hotspot related mantle plume activity. According to Molnar and Tapponnier (1975) the paleoposition of northwestern margin of Indian plate was around 23 degree south latitude, while, Klootwijk *et al.,* (1992) have given a 19 degree south latitude paleoposition during 71 Ma **(Fig. 10 and 11)**. The present paleomagnetic and rock magnetic study (Khadim *et al.,* 1996) have given a 17°± 8° south latitude for the Bibai volcanics which nearly coincides with the present position of the Reunion island in the Indian Ocean. The Reunion island and the Chagos-Laccadive ridge (Fig. 10) have been postulated to be formed in a hotspot related setting (Dietz and Holden, 1970; Whitemarsh, 1974). Backmann *et al.*,(1988) suggested a hotspot origin for both, the Chagos-Laccadive ridge and Deccan basalts (Fig. 10). Duncan and Pyle (1988) and Fisk *et al.,* (1989) have documented that the Deccan Trap and the Chagos-Laccadive ridge represent manifestation of Reunion hotspot formed by the passage of Indian continent and Indian ocean floor during 68-66 Ma respectively. The 81-57 Ma journey of Neo Tethys ocean floor, Indian continent and Indian ocean floor is illustrated in **(Fig. 12 A to D)**. The Fig. 12 A exhibits eruption of 81 Ma intra-plate volcanics (Siddiqui, *et al.,* 1996) when the Neo Tethys ocean floor passed over the Reunion hotspot. Fig. 12 B indicate the eruption 71 Ma of Bibai volcanics on the nortwestern continental shelf of Indian plate passed over this hotspot. Fig. 12 C represents the 66-68 Ma eruption of Deccan basalt within the Indian continent. The obduction of Muslim Bagh ophiolite and associated melange zone having slices of Neo-Tethys ocean floor containing 81 Mahotspot related volcanics on to the northwestern margin of Indian plate during 67 Ma. (Fig. 12 D) exhibits 57 Ma the passage of Indian Ocean floor over the Reunion hotspot and construction of the Chagos-Luccadive ridge.

9. Changes in the Paleosedimentary Environments

The sedimentary rock formation just below the Bibai volcanics is Parh Limestone (Late Cretaceous) which is micritic and sublithographic in nature and generally contains abundant radiolarian chert nodules towards its upper part. This limestone is considered to be deposited on the outer north-western shelf of Indian Continent (Fatmi *et. al.,* 1986 and Butt, 1986). The pillow lavas of Bibai volcanics are generally followed by tuffaceous sandstone or volcanic conglomerates, and at places the matrix of pillow lavas is also tuffaceous sandstone. These volcanics are overlain by sandy and marly facies of Mughal Kot Formation which is in turn followed by Pub Sandstone of Maastrichtian age. The present study suggests that just after the inception of the Bibai volcanism, the sedimentary environments on the north-western margin of Indian Plate suddenly changed from relatively deeper to shallower or even terrestrial indicated by the development of conglomerate and laterite between Parh Limestone and Paleocene Dungan Limestone in Ziarat area (Shah, 2009).

The hotspots are generally characterized by a geoid high, (1-2 km high and up to 1000 km in diameter) on astheno-lithosphere boundary that persists beneath the hotspot traces (Crough, 1983). When the north-western margin of Indian plate reached this hotspot during Late Campanian it was consequently uplifted which caused partial to complete regression of sea during Late Campanian,

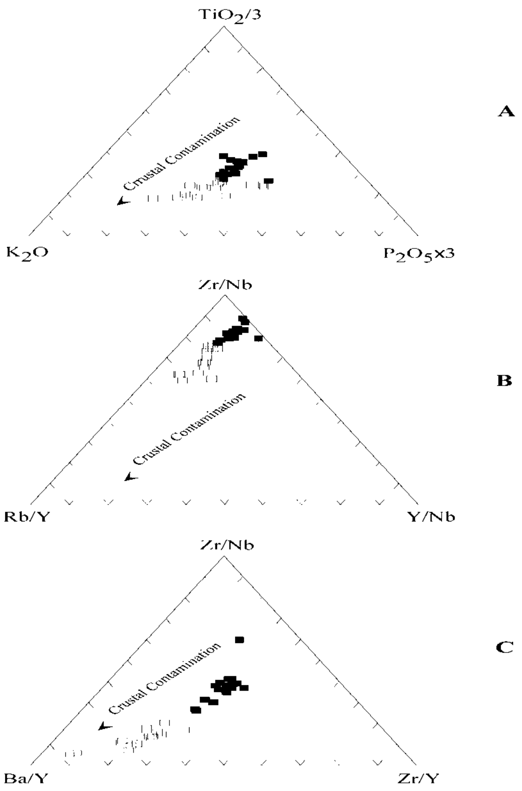

Fig. 9 (A) TiO_2-K_2O-P_2O_5 (B) Zr/Nb- Rb/Y-Y/Nb and Zr/Nb-Ba/Y-Zr/Y ternary plots for the Bibai volcanics. The open squares are for Bibai volcanics and filled squares are for 0-2 Ma Reunion island alkali basals (the Reunion chemical data is from Fisk *et al.*, 1988).

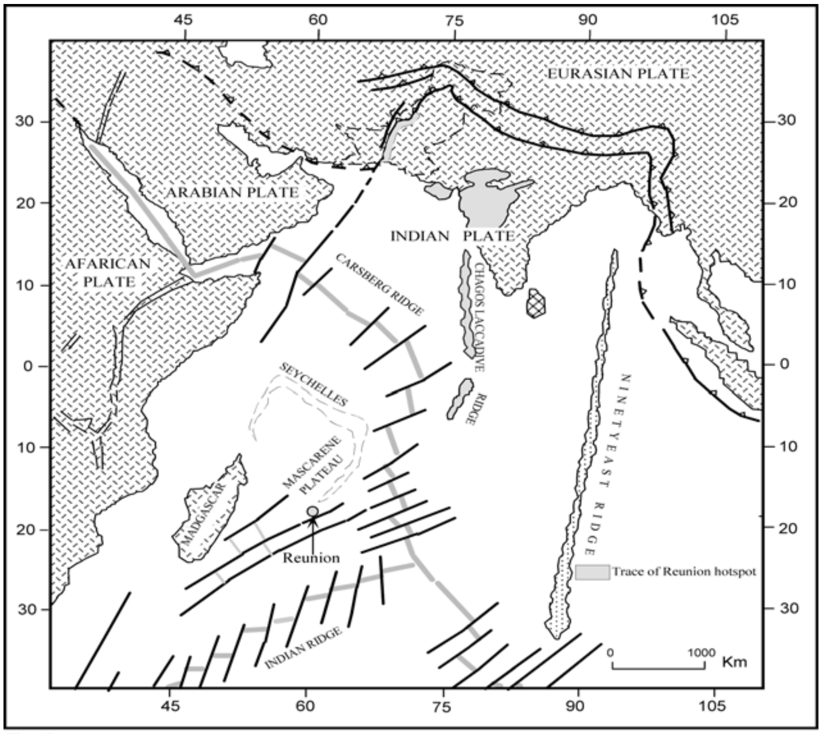

Fig. 10

Fig. 10 Tectonic map of Indo-Pakistan subcontinent and surroundings (after Condie, 1989).

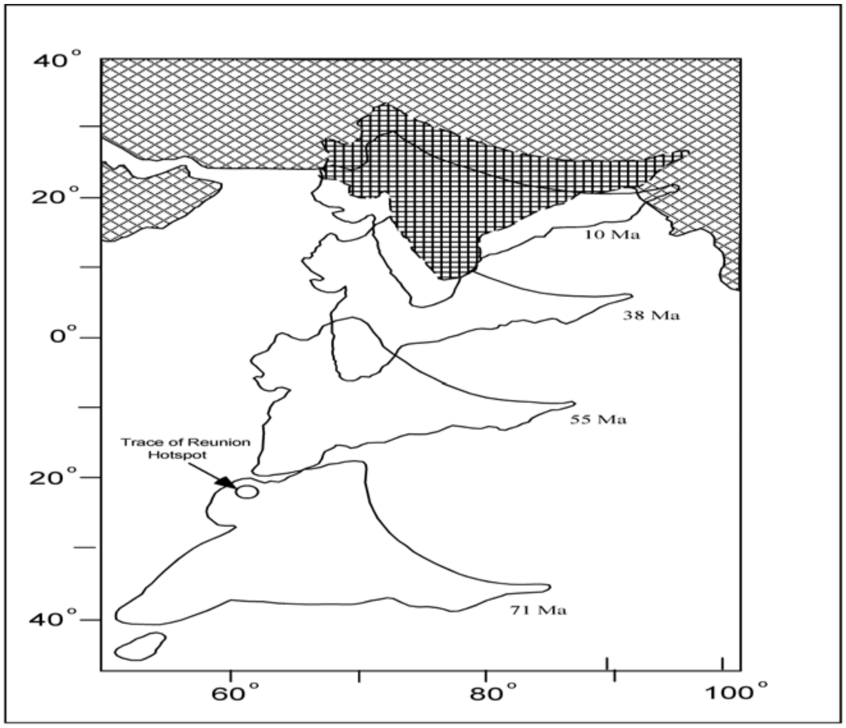

Fig. 11. The paleoposition of Indian plate during 71 Ma to 10 Ma (after Molnar and Tapponnier, 1975)

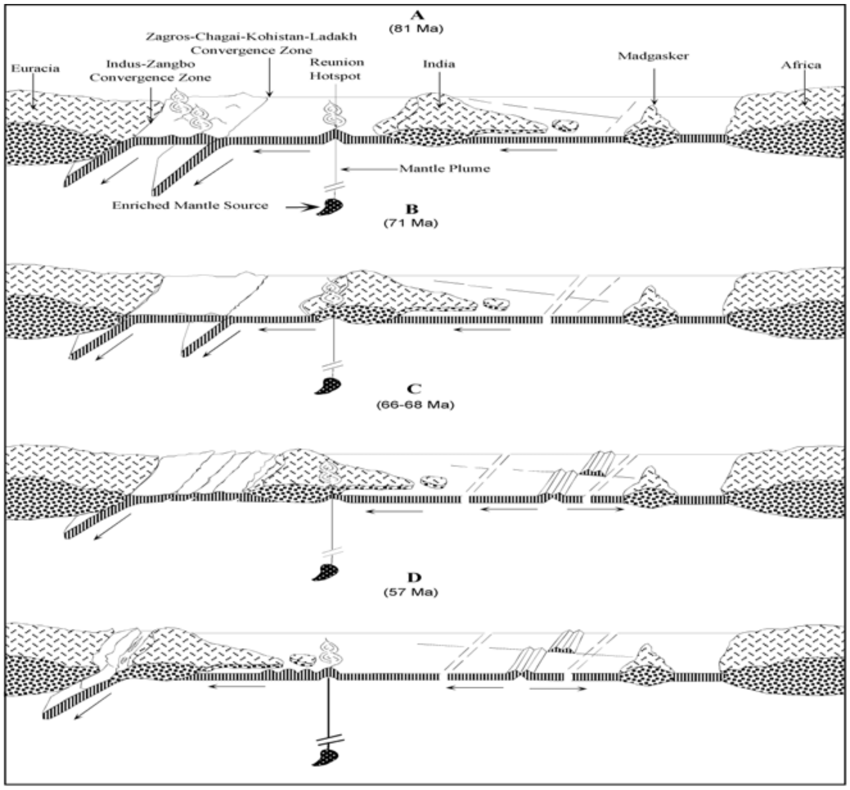

Figure 12

Fig. 12 Modal illustrating the 81-57 Ma journey of Neo-Tethys ocean floor, Indian continent and Indian Ocean floor over the Reunion hotspot. (A) Ocean floor of Neo-Tethys passing over the Reunion hotspot and eruption of 81. Ma volcanics, remnants of which now found as allochthonous blocks within the mélange zone beneath the Muslim Bagh ophiolite complex. (B) Northwestern margin of Indian plate over the reunion hotspot and eruption of 71 Ma Bibai volcanics. (C)West central part of Indian plate over the reunion hotspot and eruption of 66-68 Ma Deccan Trap volcanics. (D) Ocean floor of northern Indian Ocean passing over the Reunion hotspot around 57 Ma and eruption of Chagos Luccadive Ridge volcanics (based on the data from Siddiqui, *et al.,* 1996).

marked by the development of coarse clastic rocks included in the Bibai volcanics, Mughal Kot Formation and Pub Sandstone in some areas or laterite and ferruginous conglomerates in others. Thus the Late Campanian journey of Indian continental plate over this hotspot was responsible for the change of paleosedimentary environments on the northwestern margin of this continent.

10. Conclusions

The current petrogenetic studies suggest that the Bibai volcanics are hotspot related mildly alkaline soda-rich alkali basalts, erupted during Late Campanion (71.4 ± 3.4 Ma) due to the passage of northwestern continental shelf of Indian plate over the Reunion hotspot. The parent magma of these basalts was generated by 15% partially melted enriched garnet-lherzolitic mantle source, which was fractionated in an upper level magma chamber. The studies further suggest contamination of parent magma by the partial melts of Indian continental crust en-route to eruption and a change of sedimentary environment from neritic to littoral or terrestrial on the northwestern margin of this continent.

11. Acknowledgments

We are highly indebted to Dr. Imran Ahmad Khan, Director General, Geological Survey of Pakistan (GSP), Mr. S. Hasan Gauhar, ex-Director General, GSP and Mr. Tahir Karim Director of the same Department for their support during field and laboratory research. Mr. Jamil Ahmad of Hydrocarbon Development Institute, Pakistan is greatly thanked for the identification of some microfossils. Gratitude is also paid to Dr. Asif Khan Professor, N. C. E in Geology Peshawar University for critically reviewing the first manuscript.

References

Ahmed, Z. (1991) An oceanic island basalt from Pir Umar, Khuzdar District Pakistan. Acta Mineralogica Pakistanica, vol. **(1)**: 77-82

Allemann, F. (1979) Time of emplacement of Zhob Valley Ophiolites and Bela Ophiolites, Baluchistan (Prelim. Report). In Farah, A. and DeJong, K.A., (Eds.) Geodynamics of Pakistan, Geol. Surv. Pak., Quetta, 215-242.

Backmann, j., Duncan, R.A. (1989) Proc. ODP Init. Rep. **(115)**: 5-15.

Baker P.E., I.G. Gias, R.G Harriss and R.W. Le Maitre (1964) The Volcanological Report of the Royal Soc. Exped. to Tristen Da Cunha.

Butt A.H., (1986) Plate Tectonics and the Upper Cretaceous Biostratigraphic Synthesis of Pakistan. Acta Mineralogica Pakistanica, vol. **(2)**: 60-64.

Carmichael I.S.E., F.J. Turner and J. Verhoogen (1974) Igneous Petrology,Mcgraw Hill Book Comp., New York.

Clague, D. A. and F.A. Frey, (1982) Petrology and trace element geochemistry of Honolulu Volcanic Series,Oahu:implication for the oceanic mantle below Hawaii, J. Petrol., vol. **(23)**: 447-504

Condie K.C. (1989) Plate Tectonics and Crustal Evolution. Pergammon Press, New York.

Crough S.T. (1983) Hotspot swells. Ann. Rev. Earth Planet. Sci., vol. **(11)**: 165-193

DeJong, K.A. and A.M. Subhani (1979) Note on Bela Ophiolites with Special Reference to Kanar area; In Farah, A and DeJong, K.A., (Eds.) Geodynamics of Pakistan, Geol. Surv.Pakistan, Quetta 263-269.

Deitz R.S. and J.C. Holden (1970) The Breakup of Pangaea. Soc.Am. vol. **(221)**: 126-137.

Duncan, R. A. and D.G. Pyle (1988) Rapid eruption of Deccan flood basalt at the Cretaceous/Tertary boundary. Nature, vol. **(333)**: 841-843.

Elthon, D., J. F. Casey, and S., Komor, (1982) Mineral Chemistry of ultramafic cumulates from the north Arm Mountain massif of Bay of island ophiohite evidence for high pressure crystal fractionation of oceanic basalts . Jour of Geoph. Res. vol. **(87)**: 8717-8734.

Fatmi, A.N., I. H. Haidery, M. Anwar, and J.M. Mengal, (1986) Stratigraphy of Zidi Formation (Ferozeabad Group) and Parh Group (Mona Jhal Group),Khuzdar District, Baluchistan, Pakistan. Geol. Surv. Rec. LXXV : 32Pp.

Fischer, R.L., J.G. Sclater, and D.P. Mckenzie,(1971) The Evolution of Central Ridge,Western Indian Ocean. Geol. Soc. Am. Bull. Vol. **(82)**: 550-561.

Fisk, M. R., B. G., J. Upton, and C.E., Ford, (1988) Geochemical and experimental study of the genesis of magmas of Reunion island, Indian Ocean. Jour. Geophysc. Res. Vol. **(93)**: 4933-4950.

Frey, F. A. and D.A. Clague, (1983) Geochemistry of diverse basalt types from Loihi Seamount, Hawii: petrogenetic implications. Earth Planet. Sci.Lett. vol. **(66)**: 337-355

Frey, F. A., D. H. Green and S. D. Roy (1978) Integrated model for basalt petrogenesis: A study of quartz tholeiites to olivine melilite from southeastern Australia, utilizing geochemical and experimental petrological data: Jour. Petrol., vol. **(19)**: 463-513.

Fyfe, W. S. (1976) Hydrosphere and continental crust: Geosci. Can., vol. **(3)**: 255-268.

Gill, J. B. (1981) Orogenic Andesites and Plate Tectonics: Springer, Berlin, 189Pp.

Green, D. H. (1976) Experimental studies on a modal upper mantle composition at high pressure under water saturated and water undersaturated condions: Can. Mineral. vol. **(14)**: 255-268.

Hanson, G. N. and C. H. Langmuir, (1978) Modelling of major elements in mantle-melts systems using trace element approaches: Geochim. Cosmochim. Acta, vol. **(42)**: 725-742.

Hunting Survey Corp. Ltd. (H.S.C.), (1960) Reconnaissance Geology of Part of West Pakistan, Publ. under Colombo Plan Coop. Project, Govt. of Canada, Toronto, Canada. S.E., Humphris, G., Thompson, J.G.Schilling, and R.A., Kingsley, 1985, Petrological and Geochemical Variation Along the Mid Atlantic Ridge Between 46º S and 32º S: Influence of Tristen Da Cunha Mantle Plume. Geochem. Acta vol. **(49)**:1445-1464.

Irvine, T.N. and W.R.A. Baragar, (1971) A Guide to the Classification of the Common Volcanic Rocks. Can. Jour. Earth Soc. Vol. **(8)**: 523-549.

Jones, A.G., (Ed.) (1960) Reconnaissance Geology of part of West Pakistan. Govt. of Canada Toronto, Canada.

Kazmi, A. H. (1984) Petrology of Bibai Volcanics, in Baluchistan. Geol Bull. Unv. Peshawar. vol. **(17)**: 43-51.

Khadim, I. M., and M. N., Ali, H. Zaman, and M. Yoshida, (1996) Rock magnetic and palemagnetic studies on Upper Cretaceous Bibai volcanics in Muslim Bagh area, Balochistn: A summary Proc. Geosc.Coll. Proc Geosci Coll. 16 95-114.

Khan, W. (1986) Geology and Petrochemistry of a part of the Parh Group Volcanics near Chinjan: M Phil thesis submitted to the Centre of Excellence in Mineralogy, University of Baluchistan, Quetta, Pakistan.

Khan, W., G.R. McCormick, and M. K. Reagen (1999) Parh Group basalts of northeastern Balochistan, Pakistan: Precursors to the Deccan Traps, pp 59-74. In Macfarlane. A, Sorkhabi, R. B. and Quade, J (Eds.) Himalaya and Tebbet Mountain roots to Mountain Tops Geol. Society of America Special Paper 328.

Klootwijk,C. T., J. F. Gee, J. W. Peirce, G. M. Smith, and P. L., McFodden, (1992) An Early India-Asia contact: Paleomagnetic constraints from Ninetyeast ridge, ODP Leg. 121 Geology vol. **(20)**: 395-398.

Kojima, S., T. Naka, K., Kimura, J. M. Mengal, R.H. Siddiqui, and M.S. Bakht, (1994) Mesozoic radiolarians form the Bagh Complex in the Mulslim Bagh area, Pakistan: Their significance in reconstructing the geologic histroy of ophiolites along the Neo-Tethys suture zone. Bull. Geol. Surv. Japan. vol. 45 **(2)**: 63-97.

Le Bas, M.J., R.W LeMaitre, A., Streckeisen, and B. Zanettin, (1986) A chemical classification of volcanic rocks based on the total alkali silica diagram Jour. Petrol. vol. **(27)**: 745 50.

Le Maitre, R. W., P. Bateman, A. Dudek, J. Deller, J. Lameyre, M.J. Le Bas, P. A. Sabine, R. Schmid H. Sorensen, A. Streckeisen, A.R Woolley and B. Zanettin, (1989) "A Classification of Igneous Rocks and Glossary of Terms." Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks. LeMaitre R. W. (Edt.). Published by Blackwell Scientific Publicaions 193 Pp.

McCormick, G.R. (1985) Preliminary Study of the Volcanic Rocks of the South Tethyan, Suture in Baluchistan, Pak. Acta Mineralogica. vol. **(1)**:1-29.

McCormick, G.R. (1991) Origin of Volcanics in the Tethyan Zone of Pakistan. in Peters (Eds) Ophiolite Genesis and Evolution of the Oceanic Lithosphere.pp 715-22 Ministry of Petroleum and Minerals Sultanate of Oman.

Mckenzie, D. and J.G. Sclater (1971) The Evolution of the Indian Ocean since the Late Cretaceous. J. Geophys. Res. vol. **(25)**: 437-528.

Melson, W. T., G. Thompson, and T. H., Van Andel, (1968) Volcanism and metamorphism in the Mid-Atlantic ridge 22° N Latitude: Jour. Geophys. Res., vol. **(73)**: 5925-5941.

Meschede, M., (1986) A method of discriminating between different types of mid-oceanic rrdge basalts and continental tholeiites with the Nb-Zr-Y diagram, Chem. Geol. vol. **(56)**: 207-218.

Molnar, P. and P. Tapponnier, (1975) Cenozoic Tectonics of Asia; effects of continental collision, Science, vol. **(89)**: 419-426.

Mullen, E. D. (1983) $MnO/TiO_2/P_2O_5$: A minor element discrimination for basaltic rocks of oceanic environments and its implications for petrogenesis. Earth Planet Sci. Lett., **(62)**: 53-62.

Nakamura, N. (1974) Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and 757-75.

Naka, T., K. Kimura, J. M. Mengal, R. H. Siddiqui, S. Kojima, and Y. Sawada, (1986) Mesozoic sedimentary-igneous complex, Bagh complex in the Muslim Bagh area, Pakistan: Opening and closing ages of Cenothyan branch. Proc Geosci. Coll vol. **(16)**: 47-94.

Nisbet, E.G. and J.A. Pearce, (1977) Clinopyroxene composition in mafic Lavas from different tectonic setting. Cont. Min. Pet. vol. **(63)**: 149-160.

Otsuki, K., M. Anwar, J.M. Mengal F.A. Brohi, K. Hoshino, A.N. Fatmi, and Y., Okimura, (1989) Breakup of Gondwanaland and emplacement of ophiolite complex in Muslim Bagh area of Baluchistan. Geol. Bull. Univ. Peshawar vol. **(22)**: 103-126.

Pearce J.A. and J. R. Cann (1973) Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth. Plan. Sc. Lett. vol. **(19)**: 290-300.

Pearce, J.A. and M. J. Norry, (1979) Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. Contrib. Mineral. Petrol. vol. **(69)**: 33-47

Pearce, J. A. (1983) The role of subcontinental lithosphere in the magma genesis at destructive plate margin in, C. Hawkesworth and M. J. Eds., Noory, Continental basalts and mantle xenoliths Natwich Shiva, 230-249.

Perfit, M. R., D. A. Gust, A. E. Bence, R. J. Arculus, and S. R. Taylor, (1980) Chemical characterestics of island arc basalts, implications for mantle sources, Chem. Geol., vol. **(30)**: 227-256.

Sarwar, G. (1981) Geology of the Bela ophiolites in the Wayaro Area in Bela district south central Pakistan; Ph D. Dessertation, Univ. of Cincinnati, OH, 375 Pp.

Sawada, Y., R. H. Siddiqui, S. R. Khan and A. Aziz, (1992) Mesozoic igneous activity in the Muslim Bagh area Pakistan with special reference to hotspot magmatism related to the breakup of Gonwanaland Proc. Geos. Colloq. vol. **(1)**: 21-70.

Sawada, Y., K. Nagao, R.H. Siddiqui, and S.R. Khan, (1995) K-Ar Ages of igneous and metmorphic rocks from the Muslim Bagh area, Pakistan. Proc. Geosc. Colloq. vol. **(12)**: 73-90.

Schawarzer, R. R. and J. J. W. Roger, (1974) A Worldwide comparison of alkaline- olivine basalt and their differentiation trends.Earth. Planet.Sci. Lett. vol. **(23)**: 286-296.

Schilling, J.G., G. Thompson, R. Kingley, and Humphris, (1985) Hotspot-migration ridge interaction in the south atlantic. Nature vol. **(313)**: 187-191.

Sclater, J.G and R.L. Fischer, (1974) Evolution of the east central Indian Ocean with emphasis on tectonic tetting of the Ninety-East Ridge. Geol. Soc. Am. Bull. vol. **(85)**: 683-702.

Shah M.I. (2009) Stratigraphy of Pakistan Mem. Geol. Surv. Pak. vol. **(22)**: 381Pp.

Shervais J.W. (1982) Ti versus V plots and the petrogenessis of modern and ophiolitic lavas Eart Planet Sc Lett, vol. **(59)**: 101-108.

Siddiqui, R. H., A. Aziz,. J. M. Mengal, K. Hoshino, and Y. Sawada, (1996) Geology petochemistry and tectonic evolution of Muslim Bagh Ophiolite Complex Balochistan, Pakistan Proc Geosci Coll vol. **(16)**: 11-46.

Siddiqui R. H. J. M. Mengal, and N. Haider, (1996) Mesozoic mantle plume activites in the Neo Tethys ocean and its relationship with the break-up of Gondwanaland, Evidence from the intra plate volcanism in Muslam Bagh Area Proc Geosci Coll. vol. (16): 95-114.

Siddiqui, R. H. and J. Afzal, (1999) Late Campanian Foraminifera indicates the age of eruption of hotspot related magmatism in the Gurmai area, Balochistan, Pakistan. of abstracts First Pakistan Paleontological Convention under UNESCO-IGCP Project. 65Pp.

Sun, S.S. and W.F. McDonough, (1989) Chemical and isotopic systematics of ocean basalt, implication for mantle composition and processes. In, A.D. Saunders, and M. J. Torny, (eds), Magmatism in the ocean basins. Geol. Soc.London Spec. Pub. vol. **(42)**: 313-345.

Tarling, D.H. (1988) Gondwana Land and the evolution of the Indian Ocean p 63-77 In "Gondwana and M.G.A. Tethys" and A. Hallan, (Eds.) 317Pp. Geol Soc. Spec. Pub. 37 Pub. by Oxford Univ. Press.

Tatsumi, Y. and S. Eggins, (1995) Subduction zone magmatism. Blackwell Science, Oxford, England, 211Pp.

Thompson, R.N., M .A. Morrison, A. P. Dickin, I.L., and H. R.S. Gibson (1986) Two contrasting styles of interaction between basic magma and continental crust in the British Tertiary volcanic province. J. Geophys Res. vol. **(91)**: 5985-5997.

Vredenburg, W. W. (1901) A Geological sketch of Baluchistan desert and part of eastern Persia. Geol. Surv. Mem. India. 302Pp.

Whitemarsh, R.B. (1974) Summary of general features of Arabian Sea and Red Sea Cenozoic history. based on Leg 23 Cores. Init. Rep. DSDP, vol. **(23)**: 115-1123.

Wilson, M. (1989) Igneous Petrogenesis. Unwin Hyman, London UK, 466 Pp.

William, M.D. (1959) Stratigraphy of the Lower Indus basin west Pakistan. World Petroleum Congress, New York; Proc. Section I/**(19)**: 377-390.

Wilkinson, J. F. G. and R. W. Le Maitre, (1987) Uper mantle amphiboles and micas and TiO_2, K_2O and P_2O_5 abundances and 100 × Mg / ($Mg+Fe^{+2}$) ratios of common basalts and undepleted mantle compositions. Jour. Petrol., vol. **(28)**: 37-73.

Winchester,J.A. and P.A. Floyd, (1977) Geochemical discrimination of different magma series and their differentiation products using immobile elements, Chemical Geology, vol. **(20)**: 325-343.

Weaver, B.L., D.A. Wood, J. Tarney, and J.L. Jaron, (1987) Geochemistry of ocean island basalt from the South Atlantic, Ascension, Bouvet, St. Helena, Gongh and Tristen da Cunha. In,Alkaline Igenous Rocks, J.G. Fitten, and G. Upton, **(568)**: 253-268.

Yoder, H.S. and C.L. Tilly (1962) Origin of basalt magmas an experimental study of natural and synthetic rock systems, J. Petrology vol. **(3)**: 345Pp.