

## Petrogenesis of Eocene lava flows from the Chagai Arc, Balochistan, Pakistan and its Tectonic Implications

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**ABSTRACT:** The Eocene Lava flows occur in the northwestern part of an EW trending subduction related-magmatic belt known as Chagai arc in the western part of Pakistan. The volcanism in this arc was initiated during the Late Cretaceous, which intermittently continued up to the Quaternary period. In the regional geotectonic context this arc belongs to the Tethyan convergence zone and was believed to have formed due to the northward subduction of Arabian oceanic plate below the southern margin of Afghan micro plate and hence considered as an Andean type arc. Although Eocene volcanoclastic rock occurs throughout the Chagai arc but the lava flows only crop out in a NW-SE elongated (1 km × 6 km) area in the northwestern part of the Chagai arc. These lava flows are represented by two discrete cycles of eruptions found towards the top of the lower pyroclastic sequence of Saindak Formation of Eocene age. The older flow is about 100 m thick and extends for 2 km whereas the younger flow is 700 metre thick and extends for more than 6 km.

The lava flows are mainly represented by amigdaloidal basaltic-andesites (55.50-54.53 wt.% SiO<sub>2</sub>) and andesites (57.40-62.79 wt.% SiO<sub>2</sub>) with minor basalt (51.88 wt.% SiO<sub>2</sub>) and dacite (67.81 wt.% SiO<sub>2</sub>). The main textures exhibited by these flows are hypocrySTALLINE, porphyritic, cummulophyric, vitrophyric and sub pilotaxitic. Large phenocrysts (< 1mm - 4mm) of plagioclase (An<sub>38-58</sub>) and pyroxene are embedded in a micro to cryptocrystalline groundmass having the same minerals with devitrified volcanic glass. The phenocrysts groundmass ratio is 35:65. Apatite, hematite, ilmenite and magnetite are common accessory mineral.

Petrochemical studies reveal that these volcanics belong to medium to low K-calc-alkaline series. They have low Mg # (39-50), and higher FeO (total)/MgO (1.81-2.78) ratios, which suggest that parent magma of these rock suites was not directly derived from a partially melted mantle source but fractionated in an upper level magma chamber before eruption. The primordial mantle normalized trace element patterns exhibit marked negative Nb anomalies with positive spikes generally on K and Sr, which strongly confirm their island arc signatures. The moderate LREE enriched chondrite normalized REE patterns with negative Eu anomalies confirm their calc-alkaline character and suggests fractionation of plagioclase during differentiation. A number of plots in various tectonomagmatic discrimination diagrams together with moderate LILE/HFSE, LREE/HREE) and <sup>87</sup>Sr/<sup>86</sup>Sr ratios depict transitional character

of these volcanics between oceanic and continental margin type arcs. This is quite logical as older volcanic rocks (i.e. Late Cretaceous to Paleocene) of the Chagai arc were developed in oceanic arc environment and younger volcanics including Oligocene to Quaternary did form in continental margin setting, which suggests that after the collision of Chagai arc with Afghan block in the Latest Paleocene to Early Eocene the former converted into a continental margin. The Cr versus Y studies, moderate Zr/Y (3.68-4.91) and  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.70401-0.70402) ratio ratios suggests that these lava flows are fractionated from about 10 % partially melted transitional (slightly depleted to slightly enriched) sub-arc mantle source. A comparison of Eocene calc-alkaline rocks of the Chagai arc with their Oligocene, Miocene and Quaternary counterparts of the same arc shows a remarkable depletion in LILE and lower LILE/HFSE ratios in the former.

## INTRODUCTION

The Chagai arc is one of the economically most important mountain belts of Pakistan. Many important metal deposits including porphyry (Mo-Au-Ag), manto and vein type copper, stratiform and skarn type iron, volcanogenic gold-silver and sulphure, kuroko type lead-zinc-silver-copper are intimately associated with the magmatic rocks of this arc. The Eocene volcanic and volcanoclastic rocks occur about 15 km NW of Saindak village (Fig. 1).

The present study is the first of the systematic studies carried out on the field relations, petrography and geochemistry of the Eocene volcanic rocks of the Chagai arc. One of the principal findings of the study include realization that whereas the Oligocene to Quaternary volcanics did form in continental margin setting, the older volcanic rocks (i.e., Late Cretaceous to Paleocene) have composition which is more appropriate for their origin in an oceanic arc environment than continental margin setting (Siddiqui, 1996; 2004) while Eocene volcanic represent a transitional character between oceanic and continental island arcs.

In this paper we are presenting a detailed study of the Eocene lava flows of the Chagai

arc in terms of their petrogenesis to demonstrate their transitional character between oceanic and continental margin type arc.

### Previous Work

Vredenburg carried out pioneer geological work in the Chagai-Raskoh arc terrane as early as 1901. Hunting Survey Corporation (1960) conducted reconnaissance study and geological mapping of the entire Balochistan province on 1:253,440. During the seventies, many foreign geologists, including Sillitoe (1974), Nigell (1975), Dykstra (1978), Arthurton (1979) and Britzman (1979) visited the Chagai arc. They considered the Chagai arc as an Andean-type calc-alkaline magmatic belt, constructed on the southern leading edge of the Afghan microplate, but no petrological or geochemical data were presented in support of the hypothesis. Ahmed (1984) also upheld a similar view on the basis of major elements chemistry of some acidic intrusive rocks. Siddiqui et al. (1986, 1987, 1988) and Siddiqui (1996) performed initial petrological studies, recorded both tholeiitic and calc-alkaline magmatism and proposed oceanic island arc affinities for the Chagai arc. Regional geological mapping of the Chagai island arc on 1:50,000 scale was started in 1960, and is still in progress by the Geological Survey of Pakistan.

## GEOLOGICAL SETTING

The major part of the Chagai arc is situated in the eruptive zone of western part of Pakistan; a small part of it also extends towards west in Iran and towards north in Afghanistan. The arc is 150 km wide and stretches for 500 km EW. The Chagai arc is considered as rear arc of Chagai-Raskoh arc system (Fig. 1). Quaternary alluvium and sand dunes conceal the northern frontier of the Chagai arc. The arc is convex towards south (Spector and Associates Ltd., 1981; Farah et al., 1984) and is terminated by the Chaman transform fault zone in the east and Harirud fault zone in the west. Its southern margin. Towards south arc is bordered by an abrupt deep synclinal trough (topographic low) known as Dalbandin trough. The arc is bounded by Chaman and Harirud fault zones on its eastern and western sides, respectively. The oldest rock unit of the Chagai arc is the Cretaceous Sinjrani Volcanic Group. The Group was invaded during Late Cretaceous to Pleistocene by Chagai intrusions, represented by several phases including granite, adamellite, granodiorite, tonalite, diorite and gabbro. Other rock formations exposed in the Chagai arc are Humai formation (Late Cretaceous), Juzzak/Rakhshani formation (Paleocene), Saindak formation (Eocene), Robat Limestone (Early to Middle Eocene), Amalaf formation (Oligocene), Dalbandin formation (Miocene to Pleistocene), Buze Mashi Kok Volcanic Group (Miocene), Koh-e-Sultan Volcanic Group (Pliocene to Pleistocene) and semi to unconsolidated Subrecent and Recent deposits. The exposures of Eocene Saindak formation are found throughout the Chagai and Raskoh arc, while Eocene lava flows are only observed in the western part of the Chagai arc (Fig. 1). The generalized stratigraphic sequence in the Chagai arc is presented in Fig. 2.

The Eocene volcanic and volcanoclastic rocks are mainly developed in the lower

pyroclastic sequence of the Saindak Formation of Eocene age and occur about 15 km NW of Saindak village (Fig. 1). The volcanism is mainly represented by intercalations of volcanic conglomerate, agglomerate, tuff and tuffaceous sandstone with two lenticular flows of andesitic lava in the upper part (Fig. 3). The various volcanic and volcanoclastic rocks are described in the following:

**Volcanic conglomerates:** The volcanic conglomerates in the middle part are greenish grey to light grey in colour and constitute more than 100 m thick sequences. They are mainly composed of subangular to subrounded, 1 cm to 1 m size fragments of mainly porphyritic and amygdaloidal andesite, forameniferal limestone and tuffs, embedded in a tuffaceous sandy matrix.

**Agglomerates:** The agglomerates are light to dark green in colour and form up to 3m thick beds. They are mainly composed of subrounded, pear-shaped and well-rounded, 2.5 to 35cm size fragments of andesite, embedded in a fine tuffaceous matrix.

**Tuffs:** The tuffs and lapilly tuffs are light green to greyish green in colour and mainly composed of fine-grained, 1mm to 3cm size angular to sub-angular fragments of andesite embedded in a fine and compact volcanic ash.

**Lava flows:** The outcrops of the lava flows in the Saindak formation are elongated in northwest-southeast direction, following the axis of the famous Saindak syncline. Two, more or less identical, cycles of eruption are identified, separated by a 100m thick volcanoclastic sequence of the Saindak formation (Fig. 4). The rocks of the older cycle of eruption are about 100 m thick and extend for 2 km along the strike. The rocks of the younger cycle of eruption are up to 700 m thick and extend for more than 6 km.

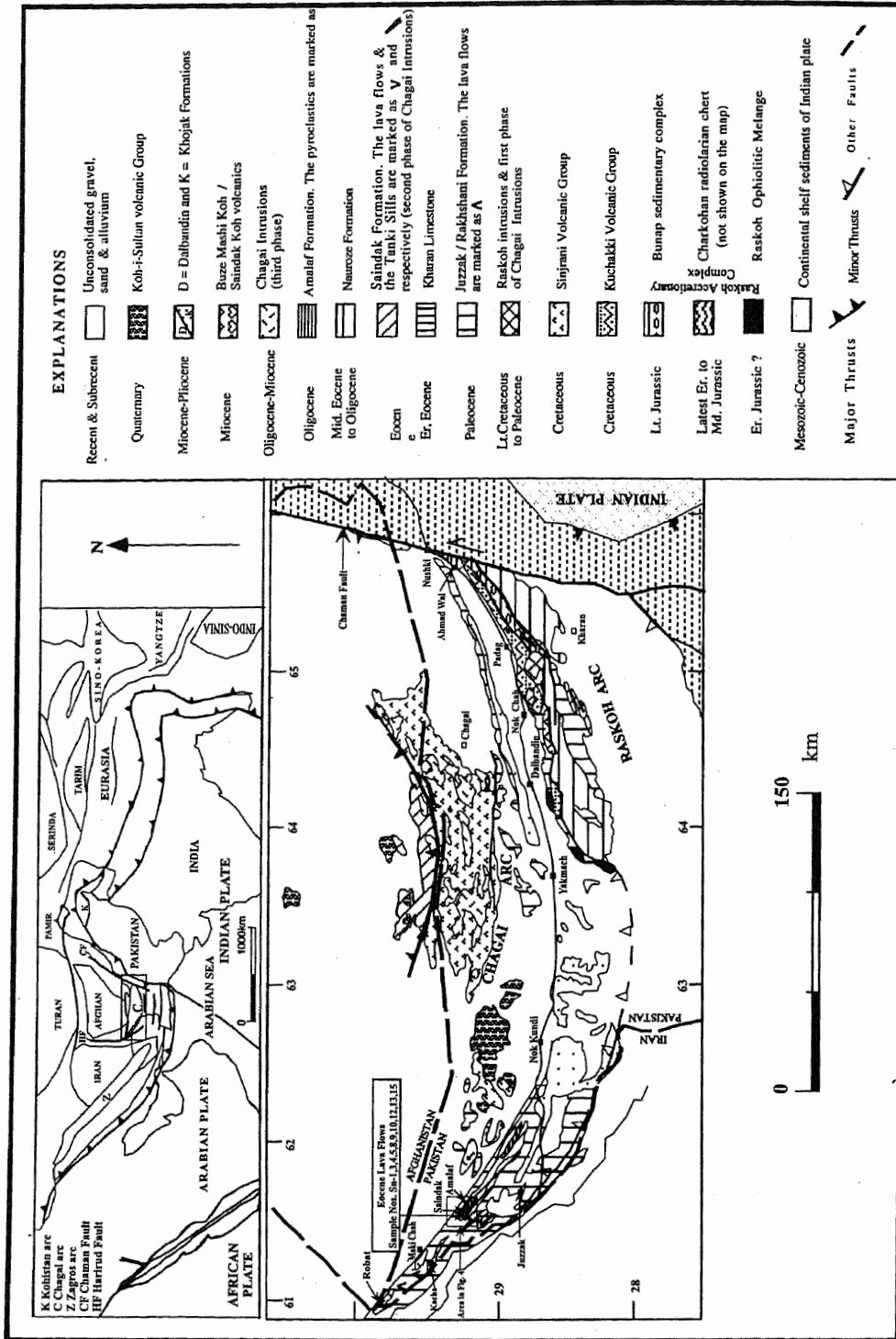


Fig. 1. Geological map of the Chagai-Raskoh arc terrane, Balochistan, Pakistan (modified and reproduced after Bakr & Jackson, 1964; Siddiqui, 2004).

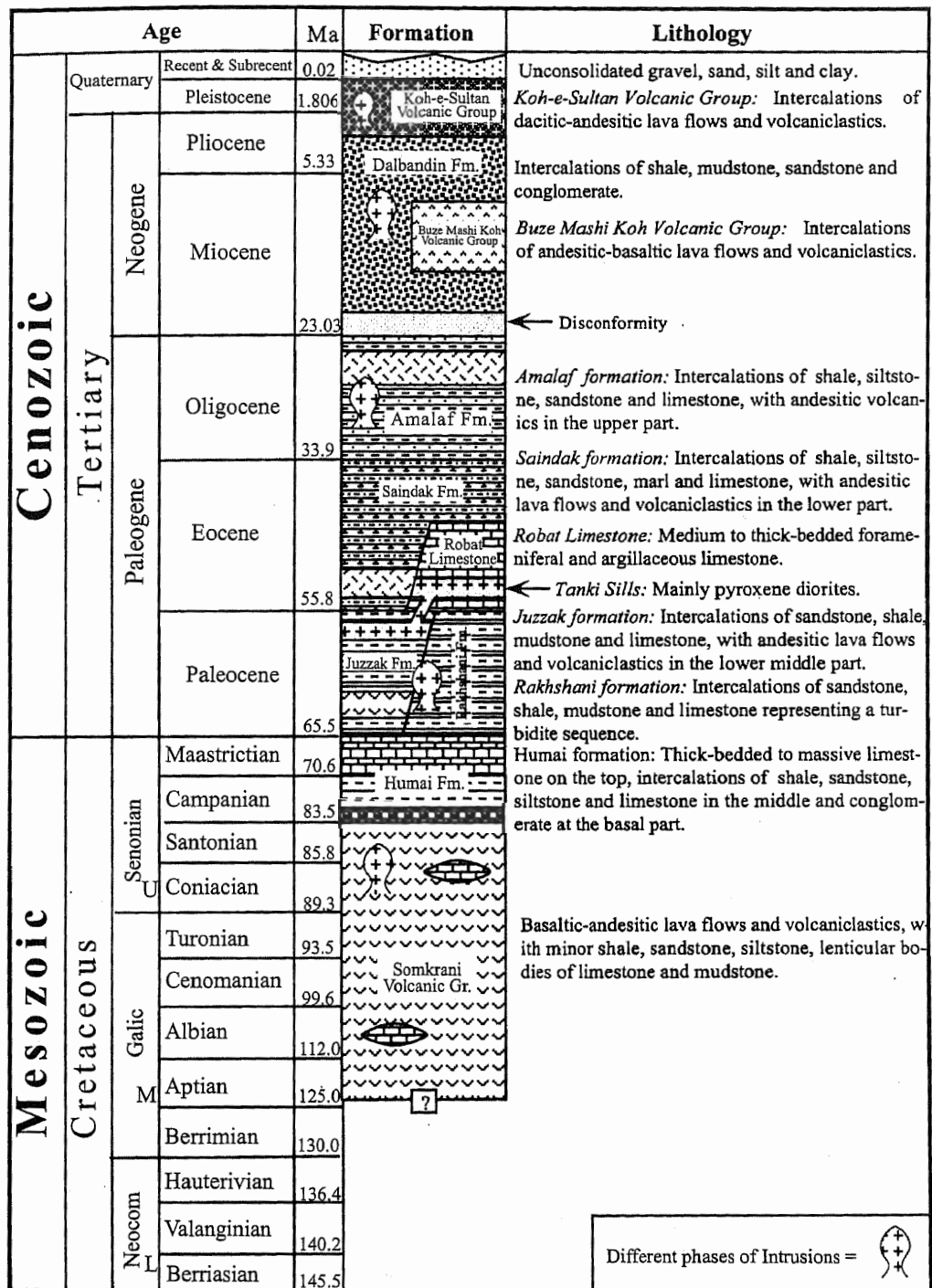


Fig. 2. Generalized stratigraphic sequence in the Chagai arc (based on Jones, 1960; Siddiqui, 2004). The ages in the time scale are after Gradstein et al. (2004).

Both the flows are transected by numerous ENE trending strike-slip faults and are folded into anticline and syncline (Fig. 4). The flows are highly weathered; at places spheroidal weathering has produced shapes that resemble pillow structures.

The flows are dark brown to black, but weather brown to maroon. They are fine-grained, hypocrySTALLINE, amygdaloidal, and porphyritic. Phenocrysts of plagioclase and pyroxenes are identifiable in hand specimen. These phenocrysts show minor argillization and chloritization. Rounded, oval and irregular vesicles are generally filled up with zeolite, chalcedony, chlorite, malachite, and crystalline quartz. At places, smoky quartz,

agate, and amethyst are also observed in cracks and cavities.

### PETROGRAPHY

Under the microscope both group of the lava flows are hypocrySTALLINE porphyritic, vitrophyric to sub pilotaxitic, and cummulophyric in texture. They are amygdaloidal and are more or less identical in texture and mineralogy except that sub-autoclastic texture is also developed in the younger flows probably due to their more intense tectonic deformation. Alteration is also more prominent in these flows. The phenocrysts to groundmass ratio ranges from 30:70 to 35:65.

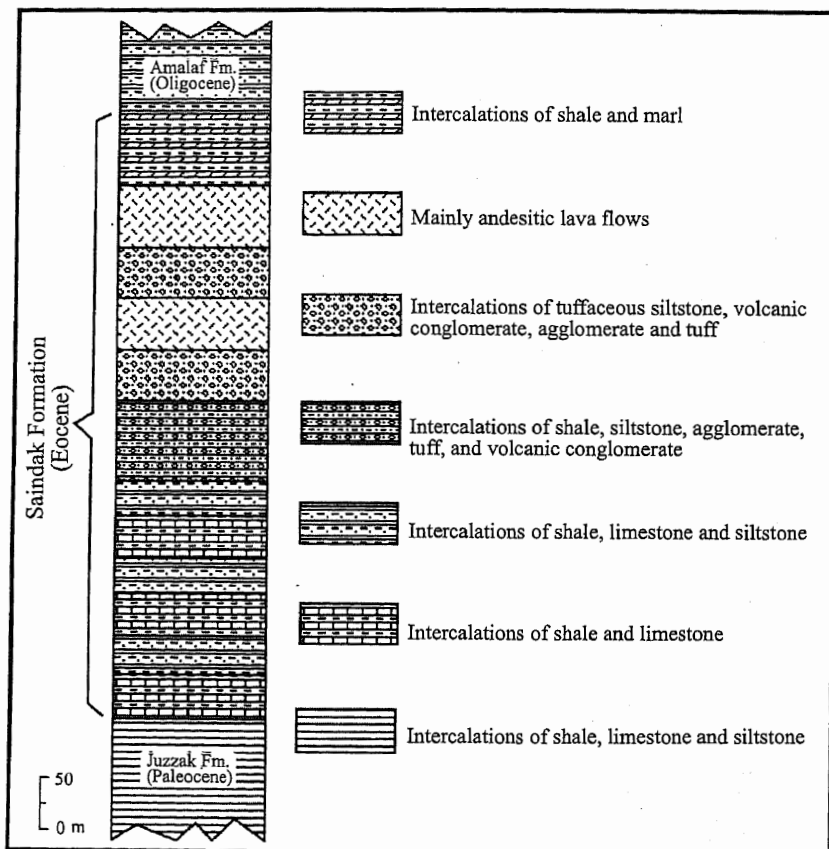


Fig. 3. Generalized internal stratigraphy of the Saindak formation in Saindak area (not to the scale).



Clusters of large (up to 4mm) phenocrysts of plagioclase and pyroxene are embedded in a micro-to cryptocrystalline and devitrified groundmass, having tiny laths (<1mm), microlites, and crystallites of plagioclase and pyroxene.

*Plagioclase:* Plagioclase crystals are euhedral to subhedral, lathlike and tabular in shape, and exhibit polysynthetic twinning according to the albite and occasionally to the combined albite and Carlsbad laws. In andesites, plagioclase phenocrysts generally range in composition from An<sub>32</sub> to An<sub>48</sub>, which falls within the andesine range, whereas in the basalt sample Sn-8 it ranges from An<sub>38</sub> to An<sub>58</sub>, suggesting albitization of labradorite. The plagioclase crystals are slightly fractured, corroded and a few (<1%) of them show resorbed and pitted margins. Oscillatory zoning is also developed in some grains. Plagioclase crystals have small inclusions of skeletal ilmenite, apatite and occasionally augite. Groundmass plagioclase occurs as small microlites, crystallites, and tiny columnar laths.

*Pyroxenes:* Both clino and orthopyroxenes are encountered in thin sections but clinopyroxene is dominant and is represented by augite, while orthopyroxene is represented by hypersthene. Augite occurs as small euhedral to subhedral prismatic grains with eight sided basal sections. It occasionally shows polysynthetic twinning and hourglass zoning. It is commonly fractured that are filled with limonite. Hypersthene occurs as small prismatic subhedral to anhedral and untwined crystals.

*Volcanic Glass:* Devitrified volcanic glass occurs in groundmass and as fillings in vesicles is generally. It is brown, yellow or green in colours and at places shows spherulitic habit and radiating appearance.

*Accessory Minerals:* Apatite, ilmenite and magnetite are common accessories. Apatite occurs as small euhedral and prismatic crystals enclosed in larger grains of plagioclase. Ilmenite occurs as small skeletal grains in the groundmass and also as inclusions in the plagioclase phenocrysts. Magnetite occurs as small subhedral and anhedral grains scattered throughout the groundmass.

*Secondary Minerals:* Secondary minerals are generally developed as partial or complete replacement of primary minerals, and as infillings in vesicles and fractures. Chlorite and uralite are the common alteration products of pyroxene. Clay mineral, sericite, and carbonates have developed after partial alteration of plagioclase.

*Amygdules:* The rocks are moderately to intensely vesiculated. Vesicles are generally filled with more than one generation of zeolites (natrolite), chlorite, chalcedony, malachite, crystalline quartz, and volcanic glass. In some vesicles, zeolites occur in the center and chalcedony, quartz, and chlorite form linings towards the margin. In others, it is reversed.

## GEOCHEMISTRY

A total numbers of ten rock samples were collected from the Eocene Lava flows of the Chagai arc. All the samples were analyzed for major and trace elements. Out of these, four samples were also analyzed for rare earth elements (REE) and one for Sr isotope. Bulk chemical analyses of the samples are given in Table 1 and Sr isotope ratios are presented in Table 2. The major elements are recalculated on a volatile free basis, because some of the sample shows loss on ignition up to 2.26 wt.% due to meteoritic alteration and infillings in vesicles as already mentioned in petrography section. The analytical techniques are presented as Appendix 1 at the end of this paper.



TABLE 1. BULK CHEMISTRY OF THE EOCENE LAVA FLOWS FROM THE CHAGAI ARC

	Sn-8	Sn-13	Sn-9	Sn-15	Sn-4	Sn-1	SN-3	Sn-5	Sn-10	Sn-12
SiO <sub>2</sub>	51.88	55.56	54.53	55.5	56.91	57.4	61.96	62.58	62.79	67.81
TiO <sub>2</sub>	1.00	1.34	1.33	1.3	1.2	1.22	1.13	1.11	1.12	0.98
Al <sub>2</sub> O <sub>3</sub>	19.6	16.41	16.68	16.77	15.55	15.75	14.43	14.54	14.14	12.8
Fe <sub>2</sub> O <sub>3</sub>	9.61	9.49	9.32	9.07	9.43	8.5	7.25	7.08	5.74	6.47
MnO	0.09	0.2	0.17	0.16	0.14	0.14	0.13	0.13	0.15	0.09
MgO	3.51	4.22	4.58	4.24	3.97	4.15	3.55	2.76	1.96	2.07
CaO	10.4	9.23	9.03	9.34	8.65	8.7	7.2	7.49	9.18	5.93
Na <sub>2</sub> O	3.17	2.94	3.42	2.95	3.17	3.07	3.19	2.85	2.67	2.67
K <sub>2</sub> O	0.57	0.28	0.61	0.31	0.66	0.7	0.79	1.13	1.6	0.86
P <sub>2</sub> O <sub>5</sub>	0.18	0.32	0.35	0.32	0.33	0.37	0.38	0.32	0.65	0.3
FeOt/MgO	2.43	2.00	1.81	1.90	2.11	1.82	1.82	2.28	2.60	2.78
K <sub>2</sub> O/Na <sub>2</sub> O	0.18	0.10	0.18	0.11	0.21	0.23	0.25	0.40	0.60	0.32
Mg #	42	47	50	48	46	49	50	44	41	39
Rb	11	6	12	9	10	11	17	27	37	29
Sr	388	483	387	446	344	341	325	346	441	302
Ba	110	153	112	137	144	139	141	158	156	91
V	276	313	321	277	272	296	253	260	269	278
Cr	57	107	132	87	194	123	216	244	243	233
Co	32	26	30	29	30	23	27	19	20	14
Ni	40	34	33	36	46	34	34	27	29	20
Zr	70	171	169	167	156	164	142	145	143	126
Y	19	34	35	34	34	38	34	34	37	27
Nb	1.8	2.8	4	4	4	3.7	3	3	3	3
Hf	1.58	3.67	—	—	—	3.59	—	3.08	—	2.59
Ta	0.16	0.17	—	—	—	0.17	—	0.21	—	0.2
Th	1.46	3.71	—	—	—	3.5	—	2.77	—	2.6
U	0.32	1.31	—	—	—	1.27	—	0.92	—	0.75
Sc	32	—	31	29	27	—	27	24	27	26
La	7.7	16.39	—	—	—	17.22	—	12.92	—	11.21
Ce	18.16	33.9	—	—	—	35.18	—	30.08	—	27.1
Nd	11.13	21.97	—	—	—	23.11	—	18.13	—	16.18
Sm	3.05	5.15	—	—	—	5.45	—	4.41	—	4.04
Eu	1.09	1.41	—	—	—	1.49	—	1.26	—	1.09
Gd	3.08	5.8	—	—	—	6.04	—	4.5	—	3.89
Er	1.92	2.79	—	—	—	3	—	2.7	—	2.27
Yb	1.7	3.42	—	—	—	3.74	—	2.25	—	2.31
ΣREE	47.83	90.83	—	—	—	95.23	—	76.25	—	68.09
Eu <sub>N</sub> /Eu*	1.09	0.79	—	—	—	0.8	—	0.87	—	0.85
Ce <sub>N</sub> /Ce*	1.03	0.94	—	—	—	0.93	—	1.04	—	1.06
(La/Yb) <sub>N</sub>	3.02	3.19	—	—	—	3.07	—	3.83	—	3.24
(Ce/Yb) <sub>N</sub>	2.72	2.52	—	—	—	2.39	—	3.4	—	2.98
(La/Sm) <sub>N</sub>	1.55	1.96	—	—	—	1.94	—	1.8	—	1.71
(La/Ce) <sub>N</sub>	1.11	1.27	—	—	—	1.28	—	1.13	—	1.08
Th/Yb	0.86	1.08	—	—	—	0.94	—	1.23	—	1.13
Ta/Yb	0.09	0.05	—	—	—	0.05	—	0.09	—	0.09
Zr/Y	3.68	5.03	4.83	4.91	4.59	4.32	4.18	4.26	3.86	4.67
Zr/Nb	38.89	61.07	42.25	41.75	39.00	44.32	47.33	48.33	47.67	42.00
Ti/Zr	85.57	46.94	47.14	46.63	46.08	44.56	47.67	45.85	46.91	46.59
Ti/V	21.70	25.64	24.82	28.11	26.43	24.69	26.75	25.57	24.94	21.12

FeOt = Total iron as FeO, Mg # = 100xMg /Mg+Fe<sup>2+</sup>, SiO<sub>2</sub>-P<sub>2</sub>O<sub>5</sub> are in %, Rb-Yb are in ppm. REE ratios with <sub>N</sub> are chondrite Normalized (after Nakamura, 1974), REE with \* are interpolated values (see text for details).

TABLE 2. Sr ISOTOPIC DATA OF ONE SAMPLE FROM THE EOCENE LAVA FLOWS OF THE CHAGAI ARC

Sample No	Estimated Age	Rb/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ (corrected: using Rb/Sr ratio and estimated age)
Sn-8a	52.0 Ma	0.028	0.70408	0.70402
Sn-8b	57.8 Ma	0.028	0.70408	0.70401
				Average 0.70402

Sr isotopic ratios were measured by VG Sector Ionization Mass Spectrometer (Micromass 3054R) with dynamic four collector analysis. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios were normalized to  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ . Repeated analyses of the NBS987 standard during the study gave  $0.710256 \pm 0.000015$  (1 sigma).

In  $\text{SiO}_2$  versus alkali (wt.%) (TAS) diagrams (after Le Bas et al., 1986), analysis of one sample plots in basalt field, four each in basaltic-andesite and andesite fields and one in dacite field (Fig. 5). The higher values of K or total alkalis ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$  wt.%) may be attributed to submarine alteration, as suggested by Melson et al. (1968) and Fyfe (1976). Therefore all the samples from Eocene volcanics are again plotted in Zr/ $\text{TiO}_2$  versus Nb/Y diagrams (after Winchester & Floyd, 1977). In this diagram all the samples plot in basaltic andesite to andesite fields (Fig. 6). The CaO contents in the rocks are also greatly variable, some of the sample show up to 10.4 wt. % due to partial replacement of some minerals by calcite and its presence as amygdules and veinlets. Similarly original contents of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and other major elements may have been changed due to alteration processes and flings of certain minerals like chlorite, chalcedony and zeolots in the vesicles. Therefore it is suggested that merely use of major elements is not appropriate and reliable for classification and petrogenetic evaluation for these rocks.

#### Major Element Abundances

The Eocene volcanics have wider and greatly variable range for  $\text{SiO}_2$  contents (51.88-67.81

wt.%). The volcanics show a variable but narrow (0.98-1.13 wt.%) range for  $\text{TiO}_2$ , and are consistent with the values (0.81-1.00) proposed for orogenic volcanic rocks (Gill, 1981). The volcanics have wider and greatly variable abundances (12.80-19.60 wt.%) of  $\text{Al}_2\text{O}_3$ . The highest value of  $\text{Al}_2\text{O}_3$ , which is represented by basalt (19.60 wt.%), is comparable with values (18-19 wt.%) of high-alumina basalts for island arc (Jacks & White, 1972). The  $\text{Fe}_2\text{O}_3$  abundances in these volcanics are high and ranges from 6.47-9.61 wt.%. The volcanics have lower but greatly variable (2.07-4.58) range for MgO, which is well below the reported (Gill, 1981; Myers, 1988) values of high magnesium basalts (>9 wt.%) and andesites (>6 wt.%). The CaO concentration is also variable and shows a wider range (7.2-10.40). The volcanics have moderate values and narrow range for  $\text{Na}_2\text{O}$  (3.01-4.49 wt.%) and  $\text{K}_2\text{O}$  (0.09-2.65 wt.%) abundances. The  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  ratios (0.11-0.60) are consistent with the reported (<0.8) ratios for oceanic island arcs (Jacks & White, 1972). The  $\text{P}_2\text{O}_5$  concentrations are higher but have variable and narrow range (0.18-0.18 wt.%). These volcanics have high  $\text{FeO}/\text{MgO}$  ratios (1.81-2.78) and low (39-50) Mg # ( $100 \times \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ), which are consistent with most volcanic rocks in orogenic arcs.

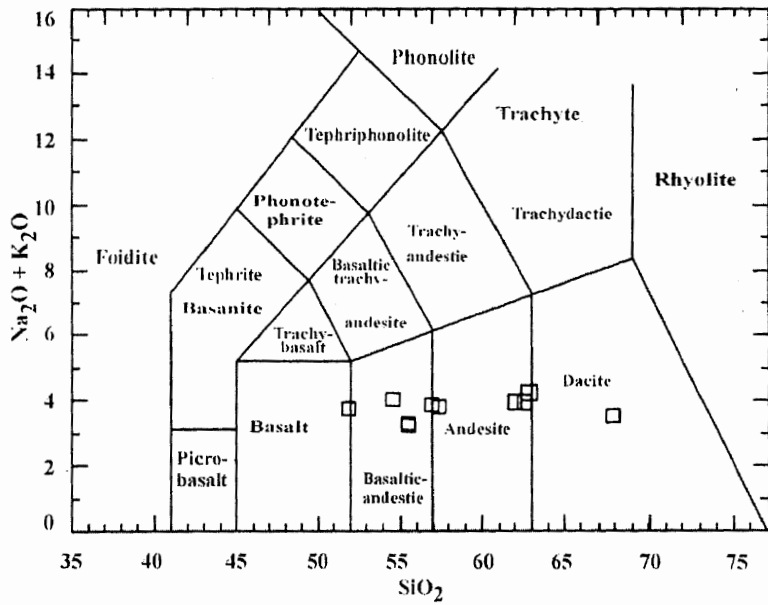


Fig. 5. Alkali versus  $\text{SiO}_2$  plot (after Le Bas, et al., 1986) for the Eocene volcanic rocks from the Chagai arc.

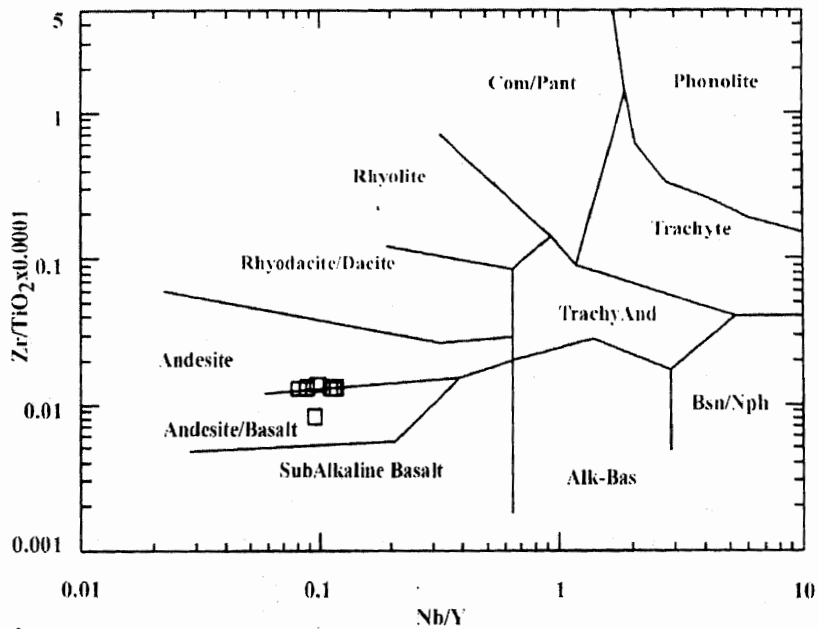


Fig. 6.  $\text{Zr}/\text{Ti}$  versus  $\text{Nb}/\text{Y}$  plot (after Winchester & Floyd, 1977) for the Eocene volcanic rocks from the Chagai arc.

### Major Element Variations

Major element oxide plots against SiO<sub>2</sub> are shown Figure 7. The negative correlation for Al<sub>2</sub>O<sub>3</sub> and CaO against SiO<sub>2</sub> are probably due to fractionation of plagioclase and those for MgO, Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> due to the fractionation of pyroxene, magnetite or ilmenite. The Na<sub>2</sub>O shows non-systematic negative correlation probably due to fractionation of plagioclase, whereas K<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub> show scattered positive correlation with SiO<sub>2</sub> probably due to the enrichment of these elements in the residual phases.

### Trace Element Variations

SiO<sub>2</sub> versus trace element variation diagrams (Fig. 8) the Eocene volcanics show scattered positive correlation for Ba, Rb and P due to enrichment of these elements in the residual liquid. The Ti, V, Sc, Co and Ni show negative correlation due to the partitioning of these elements in the ferromagnesian minerals. The negative correlation for Ti, V and Sc is probably due to the fractionation of ilmenite and magnetite, while for Co and Ni it is for the crystallization of pyroxene.

### Trace Element Abundances

*Large Ion Lithophile Elements (LILE):* The Eocene volcanics generally have higher abundances of LILE as compared to high field strength elements (HFSE). The Rb, Sr, Ba, Th and U in these volcanics ranges from 6 to 29 ppm, 302 to 446 ppm, 91 to 158 ppm, 1.46 to 2.71 ppm and 0.32 to 1.31 ppm respectively, which are consistent with medium to high-K calc-alkaline volcanic rocks orogenic arcs ((Jacks & White, 1972; Gill, 1981).

*High Field Strength Elements (HFSE):* The Ti, Zr, Nb, Y, Ta and Hf in these volcanics range from 5,870 to 8,027 ppm, 70 to 171 ppm, 1.8 to 4.0 ppm, 19 to 35, 0.16 to 0.21 and 1.58 to 3.67 ppm respectively, which are again consistent with medium to high-K

calc-alkaline volcanic rocks of orogenic arcs (Jacks & White, 1972; Gill, 1981).

### Spider Diagrams

The samples from the Eocene volcanic rocks from the Chagai arc are plotted in primordial mantle normalized spider diagram (Fig. 9) with an average trace element plot of N-MORB for comparison (both normalizing and average values are after Sun & McDonough, 1989).

In island arc basalts the LIL elements including Sr, K, Rb, Ba, Th and P are generally derived from the subducting slab and added to the sub-arc mantle peridotite source through aqueous fluids, while HFS elements including Ta, Nb, Zr, Hf, Ti, Y and Yb are derived entirely from the sub-arc mantle peridotite source (Best, 1975; Hawkesworth et al., 1977; Saunders & Tarney, 1979; Pearce, 1983; Wilson, 1989). The concentration of HFS elements remains constant and depleted relative to N-MORB, in island arc tholeiitic and calc-alkaline basalts, derived from a depleted mantle peridotite source, but the latter will have more concentrations of LIL elements. In contrast tholeiitic and calc-alkaline basalts derived from an enriched mantle peridotite source will show progressive enhancement in both LILE (excessive) and in HFSE (less) except in Ti and Y relative to N-MORB (Pearce, 1982; Wilson, 1989). The spider patterns of Eocene volcanic rocks generally exhibit progressive enrichment of all the LIL, Nb and Zr amongst HFS elements relative to N-MORB, which suggests that parent magma of these volcanics was derived from the partial melting of an enriched mantle peridotite source. The spider pattern and Table 1 also exhibit enhancement of LILE/HFSE ratios (Rb/Y, Ba/Y & Ba/Zr) in these volcanics, which are evident for an enriched mantle source.

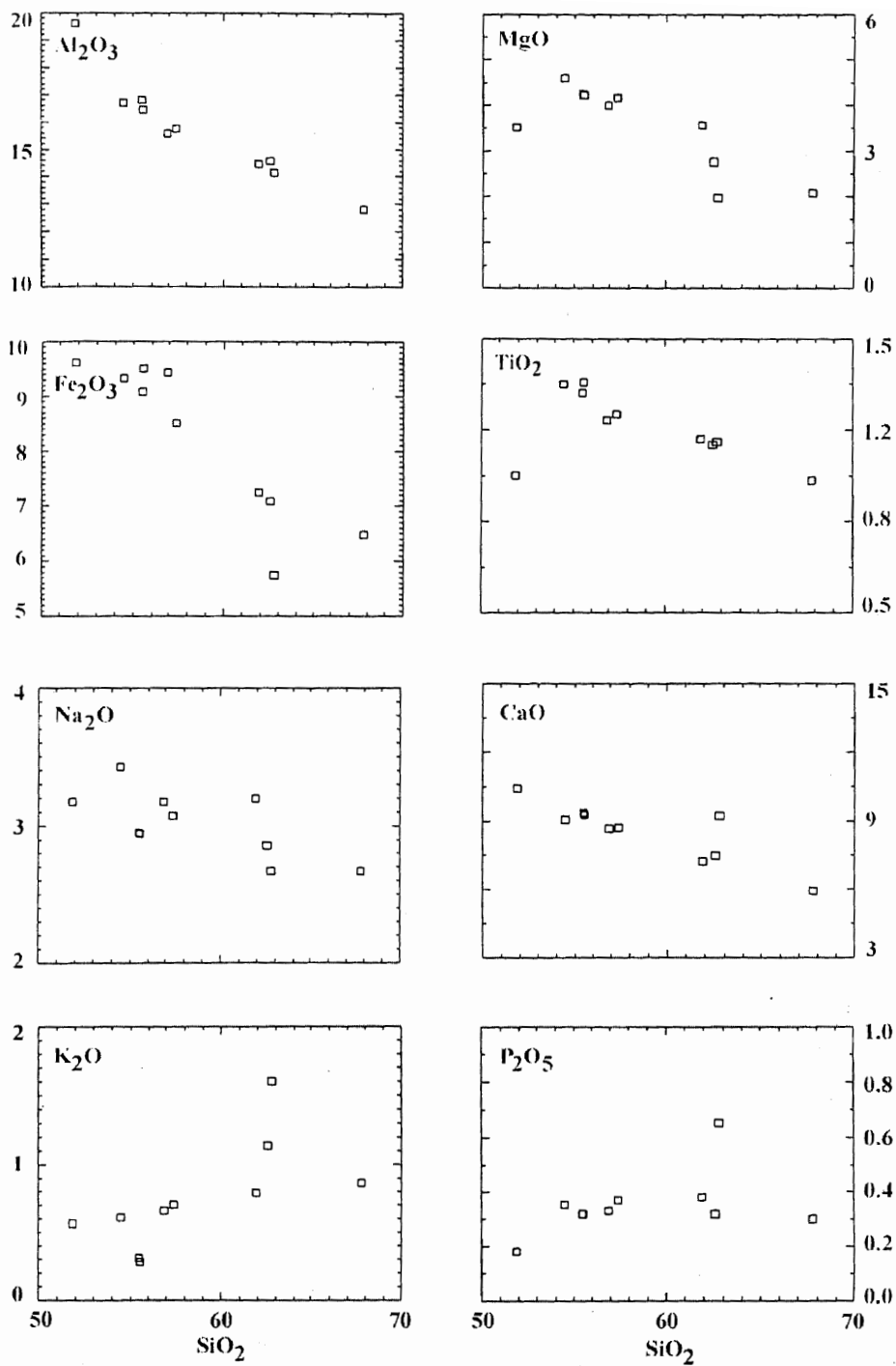


Fig. 7. Harker type variation diagrams for major elements showing fractionation trends in the Eocene volcanic rocks from the Chagai arc.

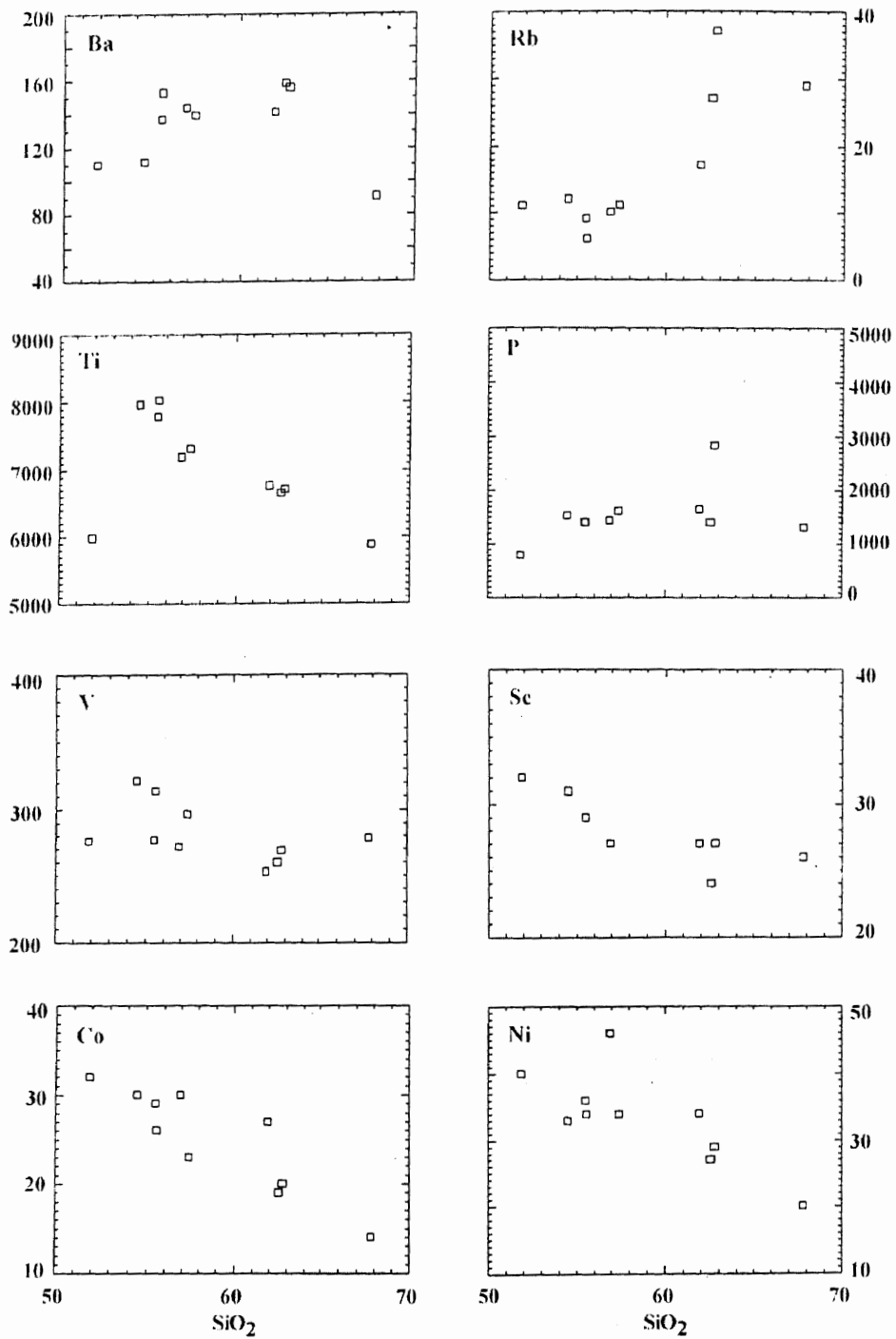


Fig. 8. Harker type variation diagrams for trace elements showing fractionation trends in the Eocene volcanic rocks from the Chagai arc.

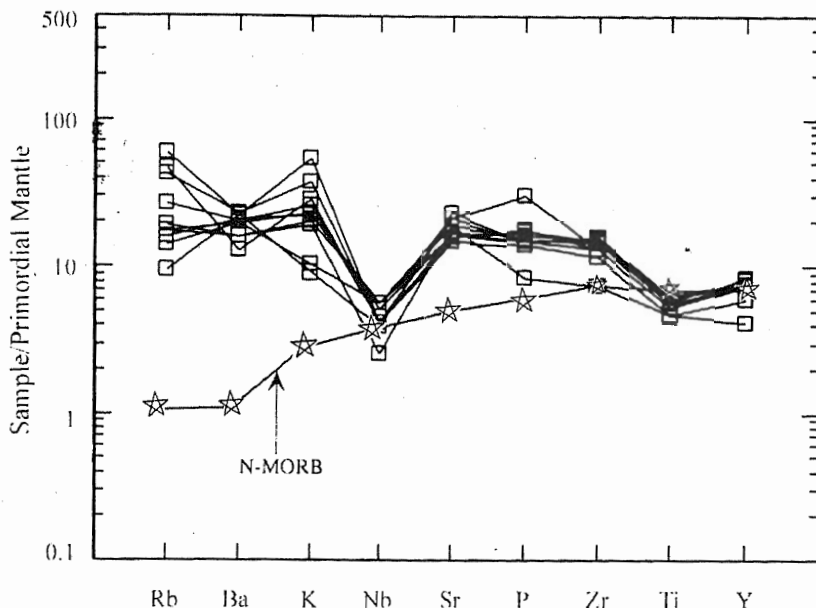


Fig. 9. Primordial mantle normalized spider diagram for the Eocene volcanic rocks from the Chagai arc. The starred pattern is for average N-MORB. Average N-MORB and normalization values are after Sun & McDonough (1989).

*Compatible Elements:* The volcanics have lower but greatly variable range of compatible elements including Cr (57-233 ppm), Ni (20-45 ppm) and Co 14-32 ppm). These values are much lower than the values proposed (Gill, 1981) for the volcanic rocks of orogenic arcs that are directly derived from the primary mantle source.

*Rare Earth Elements (REE):* The rare earth elements (La, Ce, Nd, Sm, Eu, Gd, Er & Yb) are analyzed for 5 samples (Sn-3, 5, 8, 10 & 12 to) from Eocene volcanics. All the analyzed samples have higher concentrations of light rare earth elements (LREE) as compared to heavy rare earth elements (HREE). The total REE ( $\Sigma$ REE) concentration in these volcanics is moderate and ranges from 47.83 to 65.23. The volcanics show moderately high normalized LREE/HREE ratios ( $La_N/Yb_N = 3.07$  to  $3.83$  &  $Ce_N/Yb_N = 2.39$ - $3.40$ ). They have very narrow range of  $La_N/Ce_N$

( $1.08$ - $1.28$ )  $La_N/Sm_N$  and ( $1.55$ - $1.96$ ) ratios, which suggest a slightly LREE enriched and uniform mantle source region for these volcanics. The measured Eu anomalies ( $Eu_N/Eu^*$ ) are calculated for Eocene volcanics, which are calculated (after Taylor & McLennan, 1985) by dividing the chondrite normalized ( $Eu_N$ ) values (after Nakamura, 1974) with the interpolated ( $Eu^*$ ) values [ $Eu_N/Eu^* = Eu_N/\sqrt{(Sm_N + Gd_N)}$ ] are determined for all three above mentioned volcanic groups. All the samples except basalt Sn-8, exhibit negative ( $<1$ ) Eu anomalies, which are consistent with plagioclase fractionation during differentiation. Similarly measured Ce anomalies ( $Ce_N/Ce^*$ ) are also determined for these volcanics, which are calculated by dividing the chondrite normalized (after Nakamura, 1977) Ce values by the interpolated Ce values [ $Ce_N/Ce^* = Ce_N/\sqrt{(La_N \times Nd_N)}$ ]. Two samples (Sn-1 and Sn-13) exhibit negative

(<1) Ce anomalies while the rest show positive Ce anomalies. The negative Ce anomalies indicate involvement of fluids generated by the dehydration of pelagic sediments included in the subducted slab (Gill, 1981) and are also noted in many other island arc volcanic rock suites including Japan arc (Masuda, 1968), Solomon island arc (Jacks & Gill, 1980) and Mariana arc (Hole et al., 1984). The negative Ce anomalies and relatively higher  $\Sigma$ REE concentration in two samples (Sn-1 & Sn-13) reflect their derivation from a contaminated parent magmatic source with the pelagic sediments.

#### 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.

Chondrite normalized REE diagrams (Fig. 10) of Eocene volcanic rocks of the Chagai arc show progressively enriched LREE patterns as compared to average N-MORB REE pattern (after Sun & McDonough, 1989). The HREE show variably depleted and enriched patterns as compared to average N-MORB. Two samples show distinct negative Ce anomalies, which indicate small amount of subducted pelagic sediments in the source (Hole et al., 1984). Most of the samples, except one (Sn-8), show negative Eu anomalies, which are generally linked with plagioclase fractionation during magmatic differentiation. The sample Sn-8 shows plagioclase accumulation during differentiation.

$^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios: One least altered sample from Piran Ziarat volcanics (Sn-8) is analyzed for  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratio (Table 2). The  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios determined for this sample is 0.70402.

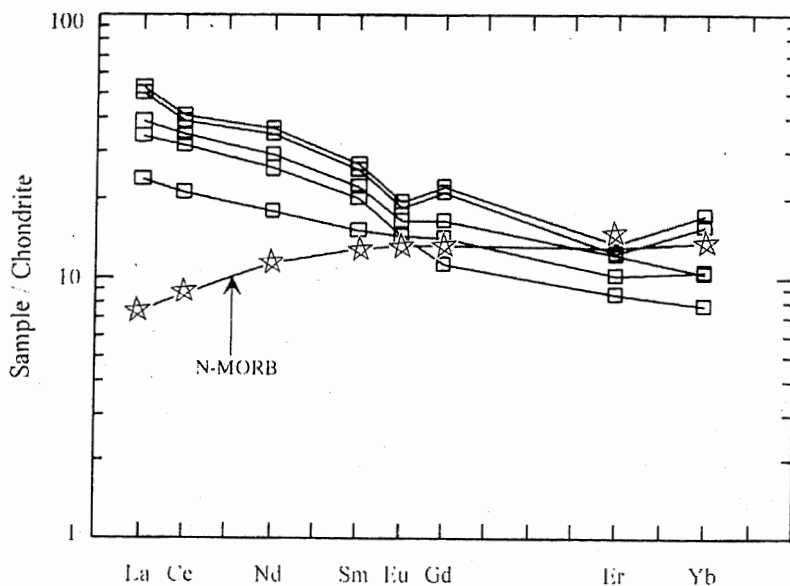


Fig. 10. Chondrite normalized REE diagram for the Eocene volcanic rocks from the Chagai arc. The starred pattern is for average N-MORB. Average N-MORB values are after Sun and McDonough (1989), whereas normalization values are after Nakamura (1974).



## PETROGENESIS

*Nature of Parent Magma:* The criteria generally used to determine whether the basaltic rocks occurring in an area represent the primary melts from the mantle peridotite source or these are the product of fractionated liquids, are:

- a) The presence of mantle peridotite (lherzolite) xenoliths within the basaltic volcanics series.
- b) The high magnesium number ( $Mg \# = Mg / (Mg + Fe^{2+})$ ) and low FeO/MgO ratios.
- c) Higher contents of compatible elements (Ni, Cr and Co).

No mantle lherzolite xenolith is encountered from Eocene volcanic rock assemblage of the Chagai arc. The Mg # in these rocks range from 39 to 50. The Ni (20-46 ppm), Cr (57-244 ppm) and Co (14-32 ppm) contents are well below the required values. Therefore, it is concluded that parent magma of these rocks have not been directly derived from an upper mantle peridotite source but have undergone olivine fractionation en route to eruption; most probably in an upper level magma chamber.

The values of trace element ratios (Table 1) including, Ta/Yb, Th/Yb and La/Yb in these volcanics are found close to the reported values (Pearce, 1983; Gill, 1981; Shervais, 1982; Wilson, 1989) of these ratios in the calc-alkaline volcanic rocks of oceanic island arcs rather than those found in the similar rocks of continental margin type arcs. The Zr/Y, Ti/Zr, Zr/Nb and Ti/V ratios are closer to continental margin type arcs, thus Eocene volcanic rocks represent transitional calc-alkaline character between the oceanic and continental margin arcs.

### Tectonic Setting

The plots in SiO<sub>2</sub> versus FeO/MgO diagram (after Miyashiro, 1974), classical FAM ternary plot (after Irvine & Baragar, 1974) and Ti-Zr-Y discrimination diagram (after Pearce, 1973)

presented in Figures 11A, 11B and 11C respectively, reveal that the Eocene volcanic rocks are calc-alkaline in nature. The Hf-Th-Ta ternary plot (after Wood, 1979) in Figure 11D indicates that these rocks were developed in an island arc setting. To determine whether these rocks were erupted in an oceanic island arc environment or produced in a continental margin type arc settings, all the sample are plotted in Zr versus Zr/Y (after Pearce, 1982), Th/Yb-Ta/Yb (after Pearce, 1983) and La/Yb versus Th (after Bailey, 1981) plots, presented in Figures 11E, 12F and 12G respectively. In Figure 11E all the samples are plotted in continental margin type arc; in Figure 11F all the samples plot within the field of oceanic island arcs but very close to the field of continental margin arcs and in Figure 11G three samples plot in oceanic island arc domain, whereas two samples in overlapping field of oceanic island arcs and continental margin type arcs. The plots in these three diagrams suggests that the Eocene volcanic rocks represent transitional character between oceanic and continental margin type arcs and the parent magma of these volcanics was generated by a slightly enriched mantle source.

The spider patterns (Fig. 9) exhibit positive spikes generally on K and Sr and exhibit marked negative anomalies on Nb, which strongly confirm island arc signatures (Pearce, 1982; Wilson, 1989; Saunders, et al., 1991). The marked negative Nb anomalies are explained by retention of this element in the residual mantle source during partial melting (Pearce, 1982; Wilson, 1989). The positive spikes or enrichment of certain LIL elements are generally considered to have formed by incorporation of these elements in the source from the subducting slab (Pearce, 1982; Wilson, 1989).

*Nature of the Source of Parent Magma:* Cr versus Y diagram (after Pearce, 1982) provides useful information about the nature of source, degree of partial melting and fractionation. Plot

of various rock samples from the Eocene volcanic rocks from the Chagai arc in this diagram indicate that these rocks are fractionated from 10 % partially melted mantle source (Fig. 11H).

The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are also used to ascertain the mantle source of parent magma as these ratios remain unchanged or exhibit very little deviation during partial melting and fractionation processes (Rollinson, 1993). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is determined for one sample (Sn-8) from Eocene volcanic rocks of the Chagai arc is 0.70402. This ratio is slightly less than the reported (Wilson, 1989) ratios for Bulk earth (0.7052). The magmas with  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios slightly less than the Bulk Earth value are considered to have derived from a slightly depleted to enriched mantle source. This again suggests that the partial melting of a transitional (slightly depleted to slightly enriched) mantle source generated the parent magma of Eocene volcanic rocks.

The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio data from Eocene volcanic rock of the Chagai arc is also plotted (Fig. 12) with a number of oceanic and continental margin type island arcs of the world. These include Tonga (Ewart et al., 1988), Mariana (Gill, 1981), Kohistan (Peterson & Windley, 1991), New Britain (Woodhead & Johnson, 1993), Aleutian (Gill, 1981), Java (McDermott & Hawkesworth, 1991), New Zealand (Ewart et al., 1988), Andes (Hawkesworth et al., 1982) and average of many oceanic island arcs (Wilson, 1989). The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of N-MORB (Sun & McDonough, 1989) and Sub-oceanic lithosphere (Vance et al., 1989) are also plotted in the same figure. The  $^{87}\text{Sr}/^{86}\text{Sr}$  data closely correlate and plot closer to the oceanic island arcs rather than continental margin type arcs.

In Table 3, average trace element chemistry of the Eocene volcanic rocks of the Chagai arc is compared with average oceanic

island arcs Mariana arc and south west Pacific arcs and continental margin type (Andes Arc). This comparison shows close affinities of Eocene volcanic rocks of the Chagai arc with oceanic island arcs rather than continental margin type arcs.

## CONCLUSION

The Eocene volcanic rocks from the Chagai arc exhibit well-developed porphyritic texture: a common feature developed in the volcanic rocks found in island arcs (Ewart, 1982; Wilson, 1989). The petrogenetic studies suggest that these rocks are calc-alkaline in nature and represent transitional character between oceanic and continental margin arcs, which is quite logical as older volcanic rocks (i.e., Late Cretaceous to Paleocene) of the Chagai arc were developed in oceanic arc environment and younger volcanics including Oligocene to Quaternary did form in continental margin setting, which suggests that after the collision of Chagai arc with Afghan block in the Latest Paleocene to Early Eocene the former converted into a continental margin. Their lower LILE/HFSE, LREE/HREE and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios indicate that their parent magma was derived from a slightly depleted to enriched mantle source and depict a transitional character. These volcanics have low concentrations (2.07-4.58) of MgO wt.%, low values (39-50) for Mg# and low contents of Co (14-32), Ni (20-46). They have enhanced LILE/HFSE and LREE/REE ratios. All these features suggest that the parent magma of these rocks have not been directly derived from an upper mantle peridotite source but have undergone olivine fractionation en route to eruption. The Cr versus Y studies and moderate Zr/Y (3.68-4.91) ratios suggest that the parent magma of these rock suites was generated by about 10 % partially melted transitional (slightly depleted to slightly enriched) sub-arc mantle source and fractionated in an upper level magma chamber.

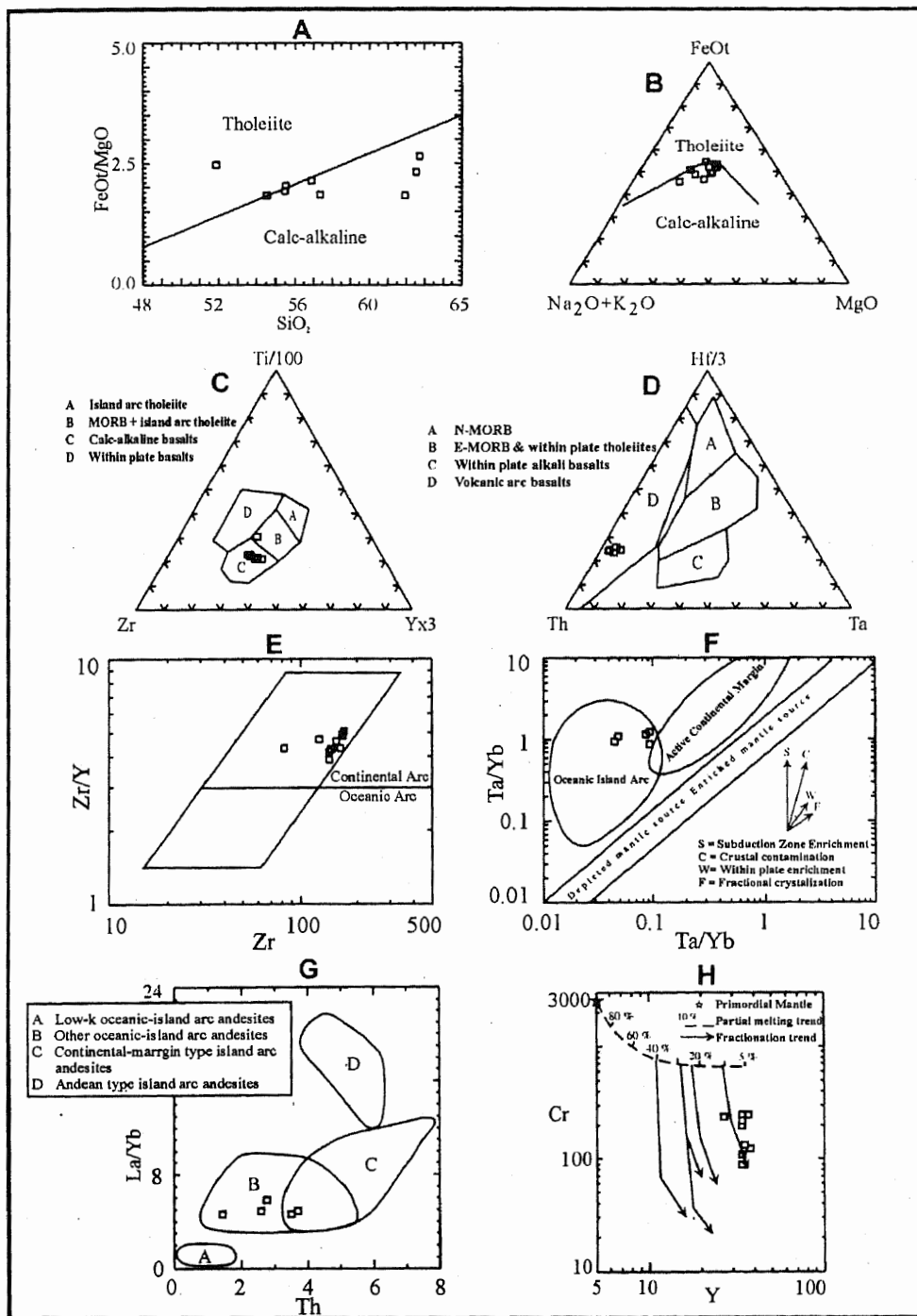


Fig. 11. A to H. Tectonomagmatic discrimination diagrams for the Eocene volcanic rocks from the Chagai arc.

TABLE 3. A COMPARISON OF AVERAGE TRACE ELEMENT CHEMISTRY OF THE EOCENE CALC-ALKALINE VOLCANIC ROCKS OF THE CHAGAI ARC WITH SOME ARC RELATED VOLCANIC ROCKS OF THE WORLD

Elements	Chagai Arc				Andes Arc				South West Pacific Arcs				Fiji Arc		New Britain Arc		Sunda Arc	
	Basalt		Andesite		Basalt		Andesite		Basalt		Basaltic desite		Andesite		Andesite		Andesite	
	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca
Ti	5990	7927	6924	6840	7620	5691	4852	4552	4133	4140	58.90	4732	4140	4140	58.90	4732	4140	4732
Rb	11	9.00	20.40	50	45	75	13.4	21.2	33.6	20	11	39	20	11	11	39	20	39
Sr	388	438.67	359.40	608	644	648	485	476	476	490	384	466	490	476	384	466	490	466
Ba	110	134.00	147.60	345	676	886	237	324	391	522	185	437	522	391	185	437	522	437
V	276	303.67	270.00	187	220	125	284	216	151	172	340	153.8	172	151	340	153.8	172	153.8
Cr	57	108.67	204.00	68	202	48	373	125	86.5	39	34	19	39	86.5	34	19	39	19
Co	32	28.33	23.80	30	31	19	48.2	28.6	21.1	16	—	—	16	21.1	—	—	—	—
Ni	40	34.33	34.00	58	67	39	146	47.1	29.0	9	23	10.8	9	29.0	23	10.8	9	10.8
Zr	70	169.00	150.00	162	179	195	68.4	103	122	114	34	84.80	114	122	34	84.80	114	84.80
Y	19	34.33	35.40	30	25	12	20.4	25.2	24.2	18	12	21.6	18	24.2	12	21.6	18	21.6
Nb	1.8	3.60	3.34	—	13	—	5.6	5.1	4.9	2	0.9	2.8	2	4.9	0.9	2.8	2	2.8
Hf	1.58	3.67	3.34	2.9	3.67	5.46	1.6	1.8	2.2	2.3	—	—	2.3	2.2	—	—	—	—
Ta	0.16	0.17	0.19	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Th	1.46	3.71	3.14	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
U	0.32	1.31	1.10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sc	32	30.00	26.25	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Cu	—	—	—	30	49.6	40	121	94.5	45.3	36	—	—	36	45.3	—	—	—	—
La	7.7	16.39	15.07	16.3	24.6	38	10.2	18.0	17.8	11	3	12.85	11	17.8	3	12.85	11	12.85
Ce	18.16	33.90	32.63	41.6	51.3	66.8	27	38.6	34.6	27	10	27.96	27	34.6	10	27.96	27	27.96
Nd	11.13	21.97	20.62	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sm	3.05	5.15	4.93	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Eu	1.09	1.41	1.38	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Gd	3.08	5.80	5.27	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Er	1.92	2.79	2.85	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Yb	1.7	3.42	3.00	2.29	2.32	1.94	1.6	1.5	1.8	—	—	—	—	—	—	—	—	—
Ti/V	21.70	26.19	25.68	36.58	34.64	45.60	17.08	21.07	27.37	24.07	10.06	30.77	24.07	27.37	10.06	30.77	24.07	30.77
Zr/Y	3.68	4.92	4.24	5.23	7.04	15.98	3.35	4.09	5.04	6.33	2.83	3.93	6.33	5.04	2.83	3.93	6.33	3.93
Ti/Zr	85.57	46.90	46.21	42.22	42.57	29.23	70.94	44.19	33.88	36.32	100.59	55.80	36.32	33.88	100.59	55.80	36.32	55.80
Zr/Nb	38.89	48.36	45.33	—	14.32	—	12.21	20.20	24.90	57	37.78	30.29	57	24.90	37.78	30.29	57	30.29
La/Yb	4.53	4.79	5.17	7.12	10.60	19.49	6.38	12.00	9.89	—	—	8.57	—	9.89	—	—	—	8.57
Ce/Yb	10.68	9.91	11.39	2.55	22.11	34.43	17.08	21.07	27.37	—	—	18.64	—	27.37	—	—	—	18.64

The values in column 1 and 2 are after Ewart (1982), in 3 and 4 are after Gill, (1981) and in 5 is after Wheller et al. (1987).  $SiO_2-P_2O_5$  are in %, Rb-Yb are in ppm

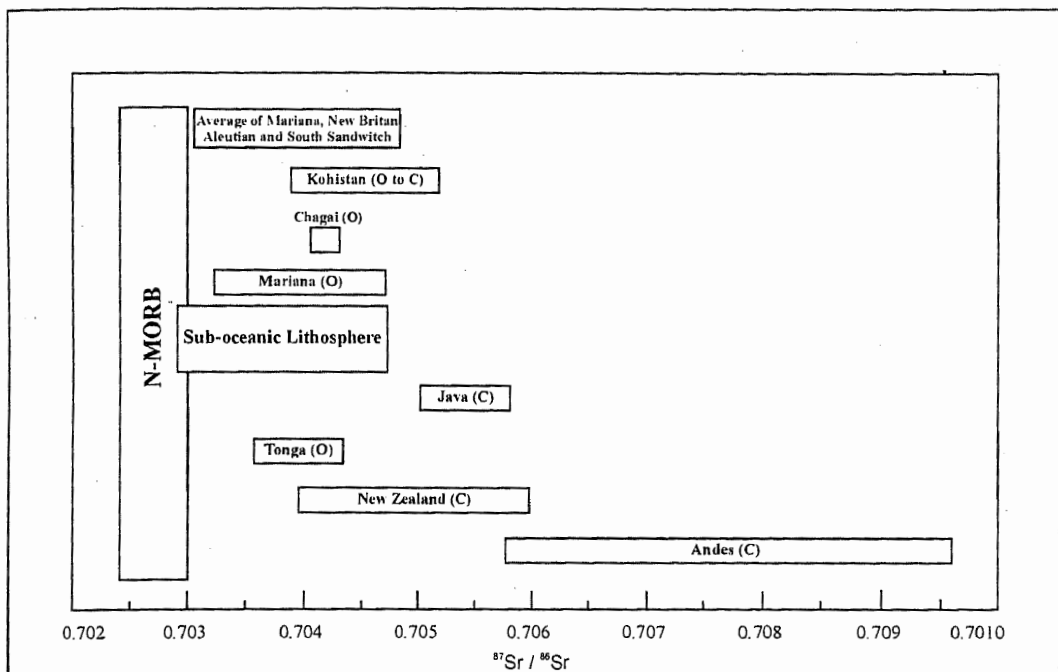


Fig. 12. A comparison of Sr isotope ratios of the Eocene volcanic rocks from the Chagai arc with different island arcs of the world. (C) is for continental margin arcs and (O) is for oceanic island arcs respectively.

## APPENDIX 1

### Analytical Techniques

#### a) Analyses of Major and Trace Elements:

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), weighing 0.7 gram was thoroughly mixed with 3.5 gram of lithium tetra borate (flux). The analyses were carried out on 1:5 rock powder and flux fused disks commonly known as glass beads. The samples thus obtained were analyzed by XRF using corresponding GSJ (Geological Survey of Japan) standard samples with every batch of ten samples. The results of analyses were then compared with the recommended values of USGS (United State Geological Survey)

standard reference samples. A check of precision of the instrument was made using JA-3 standard sample (Govindaraju, 1989).

b) Analyses of Rare Earth Elements: The analysis of rare earth elements (REE) and Hf, Th, U and Ta was carried out in the GSJ on ICP-MS 2000 (YOKOGAWA, Japan). The 0.200 g sample (<200 mesh) was weighed in a platinum dish and added 3 ml  $\text{HClO}_4$ , 4 ml  $\text{HNO}_3$  and 5 ml HF. Heated on the hot plate at  $200^\circ\text{C}$  till complete evaporation. The dish was removed from the hot plate, cooled, washed and dried. The residue was added 5 ml 1:1  $\text{HNO}_3$  and 5 ml water and gently heated on the hot plate till complete dissolution. The solution in the dish was cooled and filtered. The filtrate was transferred into a 100 ml measuring flask and added water up to 100 ml mark. The

solution thus obtained was analyzed by ICP-MS, following Imai (1990) method, using JB-1 and JA-1 as standard samples (Govindaraju, 1989) and 1.5% HNO<sub>3</sub> as blank sample. The deduction limits of ICP-MS 2000 for all these elements are <0.1 ppm. A check of precision of the instrument was made using JB-1 and JA-1 standard samples (Govindaraju, 1989).

c) *Analyses of Sr Isotopes:* The <sup>87</sup>Sr/<sup>86</sup>Sr were determined by VG Micromass 3054R mass spectrometer at GSJ, Tsukuba, Japan. About 100 mg sample (<200 mesh) was weighed in a platinum crucible and added 3 ml ultra pure water and 10 ml supper pure 40 % HF, and 5ml HClO<sub>4</sub>. The sample was decomposed on hot plate at 200°C till complete evaporation. It was added 2.5 N HCl and heated for 10 minutes. The sample was transferred in a small test tube and covered with scotch tap. Centrifuged the test tube samples at 3500 rpm for 10 minutes. Washed the cation exchange resin (CER) in the ion exchange column (IEC) by 2.5 N HCl. Transferred the test tube sample into IEC and passed it through CER. Washed twice the sample in IEC with 3 ml 2.5 N HCl. Passed through IEC 85 ml 2.5 N HCl (one hour) to separate Fe, K and other larger cations. Passed through IEC 20 ml 2.5 N HCl (half an hour) to separate Sr ions. This time smaller beakers were used to collect the sample. Transferred the sample into a small 5 ml beakers and heated the sample on hot plate till complete evaporation. Now mouth of the beaker was tightly closed with scotch tap. All the required samples and an additional GSJ standard sample (Govindaraju, 1989) were prepared following this method. The strontium isotopes in the samples were measured by VG Sector ionization Mass Spectrometer (Micromass 3054R) with dynamic four collector analysis. The <sup>87</sup>Sr/<sup>86</sup>Sr ratios were normalized to <sup>86</sup>Sr/<sup>88</sup>Sr = 0.1194. Repeated

analyses of the NBS987 standard during the study gave 0.710256 ± 0.000015 (1 sigma). A check of precision of the instrument was made using JG-1a standard sample (Govindaraju, 1989).

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