

**PETROGENETIC MODELLING OF MAFIC VOLCANIC  
ROCKS OF EASTERN HIMALAYA**

**Dissertation**

**SUBMITTED FOR THE AWARD OF THE DEGREE OF**

**Master of Science**

**IN**

**Applied Geology**

**BY**

**Nishad**

**GL6385**

**UNDER THE SUPERVISION OF**

**Dr. M. Shamim Khan**

**PROFSSOR**



**DEPARTMENT OF GEOLOGY  
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ALIGARH (INDIA)  
2021**



## CERTIFICATE

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This is to certify that **Mr. Nishad**, student of MSc Applied Geology, Department of Geology A.M.U, Aligarh has successfully completed the Dissertation work under my supervision on **“Petrogenetic Modelling Of Mafic Volcanic Rocks Of Eastern Himalaya”**. The work is original and has not been submitted in part or full for any other degree of any University or Institute. He has successfully completed his work with full devotion. During this period Mr. Nishad has critically reviewed the relevant literature related to Petrogenetic modelling and its related studies. He is also determined towards his target, result oriented and hardworking.

**Signature of the Supervisor:**  
**Dr. M. Shamim Khan**  
**Professor**  
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**Aligarh**



## CANDIDATE'S DECLARATION

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I, **Nishad**, student of Department of Geology certify that the work embodied in this MSc Dissertation is my own bonafide work carried out by me under the supervision **Dr. M. Shamim Khan** at Aligarh Muslim University, Aligarh. The matter embodied in this MSc Dissertation has not been submitted for the award of any other degree.

I declare that I have faithfully acknowledged, given credit to and referred to the research workers wherever their works have been cited in the text and the body of the report. I further certify that I have not willfully lifted up some other's work, para, text, data, result, etc. reported in the journals, books, magazines, reports, dissertations, thesis, etc., or available at websites and included them in this MSc Dissertation and cited as my own work.

**Date:** .....

(Signature of the candidate)

**Nishad**

(Name of the candidate)

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I express my deep gratitude and respect to my supervisor **Dr. M. Shamim Khan** for his keen interest and valuable guidance, strong motivation and constant encouragement during the course of the work. I thank for his great patience, support and useful suggestions and his valuable guidance to me.

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I would like to convey my sincere gratitude to all my friends and colleagues, especially, **Mr. Abdul Latheef** and **Mr. Ali Shahin V.M.** for their support and feedbacks.

**(Signature of the candidate)**

**Nishad**

**(Name of the candidate)**

*Dedicated to*  
*My Teachers and Family*

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# CHAPTER ONE

## 1. INTRODUCTION

We are seldom favored to make direct observations of the processes governing rock compositions, because of where those processes occur, the times at which they occur, and the time scale over which they take place. Instead, we rely on circumstantial evidence in accessible materials and attempt to construct self-consistent pictures of events that took place and the nature of the starting materials. One important type of evidence is the natural rock samples exposed on the surface. Their mineralogy and chemical composition give us first hand information about the cumulative action of the processes responsible for the generation, evolution and emplacement. For igneous rocks, trace element abundances in general and REE abundances in particular act as robust clues about their being and existence.

REE abundances are effectively used to model the source composition, degree and type of melting and subsequent crystal fractionation (Haskin, 1984). "Modelling" means a well-defined description of REE behavior during the process of magma or rock formation. Predictions of a model may be compared with observed REE abundances in a rock or magma, if the model includes a description of the starting material. Alternatively, the modelling may be inverted and the REE abundances in the rock or mineral used to predict the nature of the starting material. In either case, the conclusions of the exercise are "model dependent", i.e., valid only to the extent that the composition-producing process was correctly identified and the chemical behavior of the REE during that process was adequately described. The geochemical behavior of REE is intrinsically interesting, but use of REE abundances in determining evolutionary histories of suites of rocks is even more interesting and important.

The present study is aimed at establishing the geochemical character of mafic rocks to decipher their petrogenesis and tectonic environment.

## CHAPTER TWO

### 2. GEOCHEMISTRY

To understand to describe petrogenetic modeling, analysis of twenty mafic volcanic rock samples have been taken from published literature and presented in the table 1.

#### 2.1 Assessment of Element Mobility

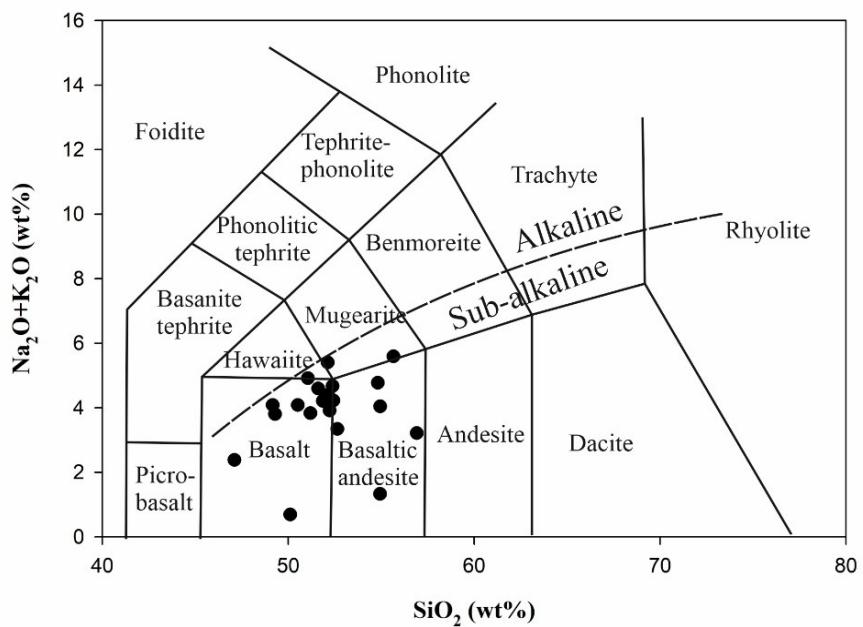
The trivalent rare earth elements and the high field strength elements (HFSE) such as Th, Hf, Nb, Ta, Zr, Ti, Y are not significantly affected by the alteration and are immobile during low grade metamorphism (Mahoney et al. 2000). This is shown by the consistancy of HFSE/LREE ratios, such as Th/La, Hf/Sm, Nb/Ce and Zr/Sm. However, where alteration has been extreme, the REE have been leached and redeposited by carbonate rich and K rich metasomatic fluids, while Zr, Ta and Ti have unchanged (Ludden et al. 1982).

The Ni content is similar in altered and least altered samples, and V, TiO<sub>2</sub> and SiO<sub>2</sub> are apparently not affected by alteration. Various elements are plotted against Zr show non-systematic variation with K<sub>2</sub>O, Na<sub>2</sub>O, CaO, Rb, Ba and Sr probably indicating their mobile nature (Table 1). Negative anomalies of Rb, K and Sr in the certain samples may be due to surface alteration, as these elements are typically mobile and not attach any petrogenetic significance in the present observation. However, since these elements are affected to the similar degree during alteration processes, their ratios (Rb/Sr, Ba/Sr, K/Rb) are comparable.

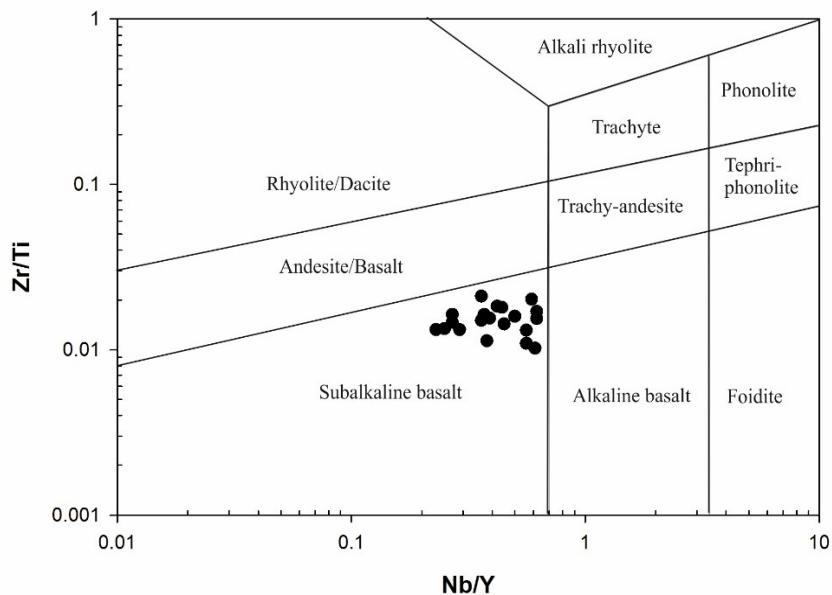
The abundance of Ca, Na, K, Rb, Ba and Sr appears to have modified during alteration and low-grade metamorphism. Hence, the Alteration Index for these samples was calculated. Only one among the samples (sample M16 117) shows a higher alteration index of 59.07 wt% which suggests that the alteration process has influenced the major element abundances of these rocks. All the LOI values are > 1 wt.% and reach much higher values in the altered basalt. Tholeiitic basalts show low AI values, indicating least affected by secondary alteration processes as compared to alkaline basalt. It is generally accepted that AI values of about 35±10 are characteristic of pristine MORB and arc- related volcanic rocks (Lafleche et al. 1992). Sage et al. (1996) also reported chloritisation and/or seritisation can produce higher AI (>50) and altered mafic volcanic rocks which are komatiitic or olivine rich may have AI values as high as 85±10 whereas albitisation produces lower AI (<30).

## 2.2 Magma Classification:

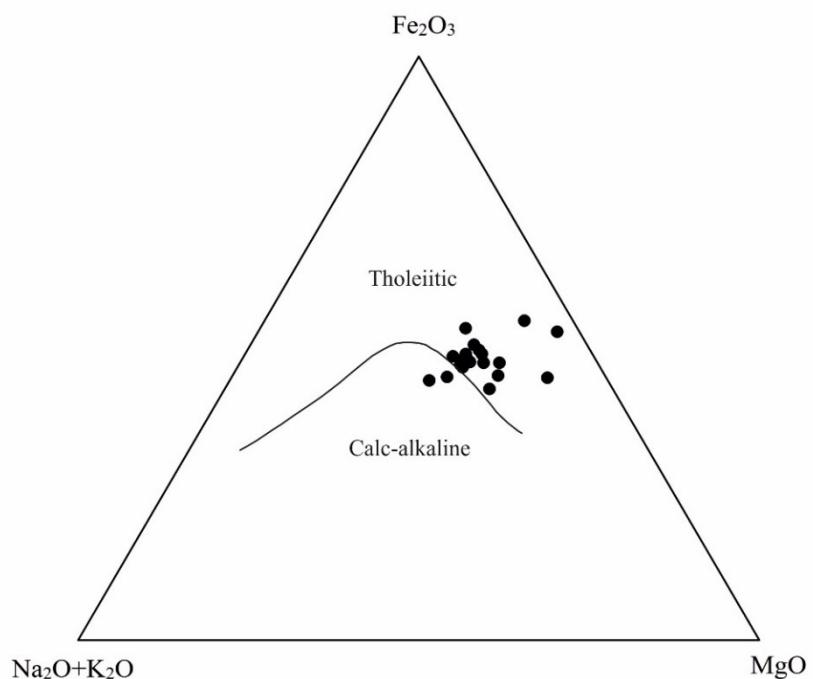
In order to classify magma, two most commonly used diagrams TAS (Le Bas et al., 1986) and AFM (Irvine & Baragar 1977) and Zr/Ti – Nb/Y (Pearce, 1996) have been used. The use of these diagrams eliminates the possibility of misinterpretation that may arise due to susceptible nature of alkalies. It's evident from these diagrams (Figures 1, 2 and 3), that all the samples exclusively fall in the sub-alkaline field. The low Nb/Y ratio (<0.7) of these rocks is another testimony of their being subalkaline rocks (Pearce & Gale 1977). Therefore the samples collected are all of sub-alkaline basaltic rock. That too dominantly under basalt and a little samples categorized under andesite.



**Fig.1** SiO<sub>2</sub> vs. Na<sub>2</sub>O+K<sub>2</sub>O diagram



**Fig.2** Nb/Y vs. Zr/Ti diagram



**Fig.3** AFM diagram

From the AFM diagram (Fig.3) plotted in ternary plot clearly decipher that almost all the samples are of tholeiitic basaltic type except samples M5 65 and M6 93. The subalkaline are

plotted within the tholeiitic field. As the Ti/Y ratio does not show variations during fractional crystallization, Ti/Y ratio has been used to classify the magma type (Peate et al. 1992).

Alkaline basalt is characterized by enrichment of  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$ ,  $\text{K}_2\text{O}$ ,  $\text{Sr}$ ,  $\text{Th}$ , HFSE, REE, LREE and depleted in  $\text{SiO}_2$ ,  $\text{Na}_2\text{O}$ ,  $\text{Al}_2\text{O}_3$  with insignificant Eu anomaly. The tholeiitic character is indicated by enrichment of large ion lithophile elements (LILE) and light rare earth elements (LREE) and depleted of  $\text{Nb}$ ,  $\text{P}$ ,  $\text{Ti}$ ,  $\text{Nb}/\text{Y}$  ratio.

**Table 1.** Geochemical abundance of mafic rocks (major elements in wt%)

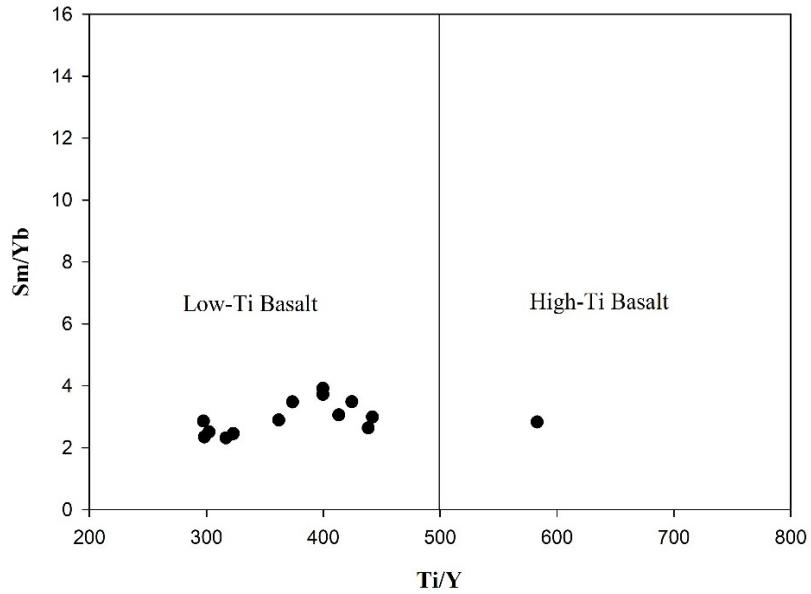
Sample Nos.	M1 42	M2 43	M3 44	M4 63	M5 65	M6 93	M7 94	M8 130	M9 131	M10 136	M11 122	M12 126	M13 148A	M14 22	M15 127	M16 117	M17 139	M18 146	M19 133	M20 134
SiO <sub>2</sub>	49.28	52.38	52.42	51.05	55.65	52.12	51.6	49.16	50.51	51.19	54.81	52.14	52.64	56.91	54.94	47.1	50.1	54.93	51.85	52.22
TiO <sub>2</sub>	1.67	1.9	1.77	2.1	2.01	1.84	1.85	2.44	2.4	2.4	2.87	1.95	1.78	1.84	1.83	1.85	1.59	1.63	2.45	2.82
Al <sub>2</sub> O <sub>3</sub>	13.31	14.99	14.14	14.8	13.45	14.61	14.54	13.33	13.33	14.51	14.77	13.95	13.93	12.04	14.11	13.12	13.91	14.23	14.19	13.8
Fe <sub>2</sub> O <sub>3</sub>	10.96	10.81	10.61	11.55	9.48	10.44	10.67	12.33	11.6	11.65	11.34	11.23	11.02	9.79	10.33	12.38	11.17	10.2	11.1	12.73
MgO	9.44	7.65	7.16	7.3	6.25	7.33	7.36	8.74	8.74	7.99	10.25	7.95	8.84	6.35	7.11	12.79	9.29	7.11	7.34	7.2
CaO	6.89	7.22	7.62	6.61	6.12	5.74	7.23	7.67	7.67	8	7.57	6.27	7.12	5.34	7.19	7.16	10.2	9.79	7.38	6.77
Na <sub>2</sub> O	3.53	3.08	2.92	3.14	3.12	3.54	3.59	2.74	2.74	3.52	3.33	3.95	2.77	2.9	2.93	1.98	0.64	1.24	3.99	2.59
K <sub>2</sub> O	0.27	1.59	1.3	1.77	2.47	1.86	1	1.34	1.34	0.31	1.44	0.45	0.57	0.31	1.11	0.4	0.05	0.09	0.22	1.32
MnO	0.15	0.13	0.14	0.15	0.11	0.15	0.15	0.17	0.15	0.19	0.17	0.14	0.13	0.12	0.13	0.15	0.13	0.11	0.15	0.17
P <sub>2</sub> O <sub>5</sub>	0.21	0.21	0.2	0.25	0.22	0.29	0.29	0.27	0.41	0.38	0.25	0.26	0.19	0.21	0.25	0.22	0.23	0.2	0.31	0.28
LOI	3.88	1.8	2.01	2	1.98	3.46	3.21	3.11	2.32	1.11	3.66	3.01	2.88	3.54	1.44	3.91	2.13	0.46	1.5	1.36
Total	99.59	101.7	100.3	100.7	100.86	101.4	101.5	101.3	101.21	101.25	100.21	101.3	101.87	99.35	101.37	101.06	99.44	99.99	100.48	101.26
Na <sub>2</sub> O+K <sub>2</sub> O	3.8	4.67	4.22	4.91	5.59	5.4	4.59	4.08	4.08	3.83	4.77	4.4	3.34	3.21	4.04	2.38	0.69	1.33	4.21	3.91
Fe <sub>2</sub> O <sub>3</sub> /MgO	1.16	1.41	1.48	1.58	1.52	1.42	1.45	1.41	1.33	1.46	1.11	1.41	1.25	1.54	1.45	0.97	1.20	1.43	1.51	1.77
CaO/TiO <sub>2</sub>	4.13	3.80	4.31	3.15	3.04	3.12	3.91	3.14	3.20	3.33	2.64	3.22	4.00	2.90	3.93	3.87	6.42	6.01	3.01	2.40
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	7.97	7.89	7.99	7.05	6.69	7.94	7.86	5.46	5.55	6.05	5.15	7.15	7.83	6.54	7.71	7.09	8.75	8.73	5.79	4.89
Fe <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	6.56	5.69	5.99	5.50	4.72	5.67	5.77	5.05	4.83	4.85	3.95	5.76	6.19	5.32	5.64	6.69	7.03	6.26	4.53	4.51
CaO/Al <sub>2</sub> O <sub>3</sub>	0.52	0.48	0.54	0.45	0.46	0.39	0.50	0.58	0.58	0.55	0.51	0.45	0.51	0.44	0.51	0.55	0.73	0.69	0.52	0.49
Alt. Index	48.24	47.29	44.53	48.19	48.55	49.76	43.59	49.19	49.19	41.88	51.75	45.11	48.76	44.70	44.82	59.07	46.28	39.50	39.94	47.65
Mg#	64.35	59.73	58.58	56.98	58.01	59.54	59.11	59.77	61.23	58.97	65.45	59.74	62.70	57.62	59.06	68.41	63.55	59.37	58.09	54.24

**Table 2.** Geochemical abundance of mafic rocks (trace elements in ppm)

Sample Nos.	M1 42	M2 43	M3 44	M4 63	M5 65	M6 93	M7 94	M8 130	M9 131	M10 136	M11 122	M12 126	M13 148A	M14 22	M15 127	M16 117	M17 139	M18 146	M19 133	M20 134
<b>Rb</b>	3	45.5	34	54	42.2	24.2	23.9	36.2	28	28	3.8	24.5	13.1	5.6	22.8	5.5	17.2	15.3	4.4	19
<b>Nb</b>	8.4	11.2	5.4	14.7	12.9	12.6	13.3	16.4	22.4	22.4	13.3	17.9	8.3	7.1	13	10.5	20.3	9	15.2	11.3
<b>Sr</b>	311	399	209.2	319	376	544	549	831	748.6	748.6	321.4	499.2	280	313	393	665.8	521.1	321	368.5	510
<b>Ba</b>	121.3	317	221.4	350	516	701	386	260	866	295.2	122.7	281	206	228	400	176.2	126	138	255	343
<b>Ni</b>	102	44.3	47	20	48.6	4.7	3.7	104.8	39.1	15.2	434.7	47.4	57.3	19.5	41.4	233	54.6	44.4	7.3	36.4
<b>Cr</b>	557	254	857	148	265	610	82	459	216	231	749	246	325	211	232	976	266	187	111	163
<b>Zr</b>	163	150	140	227	172	223	234	233	221	244	175	153	143	161	165	203	104	110	240	262
<b>Zn</b>	119	125.8	125	130	92.4	129.1	125.5	126	130.1	135	106.5	127.2	117.3	109.9	114.7	126	120	100.3	132.1	145.3
<b>V</b>	176	148	169	220	175	156	121	224	212	189	164	179	141	151	160	175	150	25	180	203
<b>Y</b>	31	38.2	23.1	33.7	28.4	21.5	37.3	33.1	36	36	21.9	32	33.7	26.7	36.3	25.3	36.1	24	40.6	29
<b>U</b>	0.5	0.6	0.2	1.7	1.4	0.9	0.8	0.6	1.1	0.2	0.5	0.1	0.2	0.4	0.4	0.3	0.1	0.1	0.2	0.7
<b>Th</b>	1.8	1.5	1.5	2	1.5	2.3	4	1.8	2.8	3.1	1.4	2.6	1.3	0.8	1.8	1	2.5	2.6	3.7	1.9
<b>Sc</b>	20	20.8	19	34	15.6	17	15.8	23	21.5	21.5	18	18.4	18.3	20	17.1	15.5	20.7	20.8	17.1	24.1
<b>Cu</b>	13	30.9	21	10	18.6	3.3	4.2	22.1	16.8	7	24.6	14.3	10.6	8.2	11.8	19	16.2	13.1	5.4	10
<b>Co</b>	35	28.4	36	35	36.1	35.6	35.1	40.1	43	32.1	52	35.2	26.5	28	28.5	43	32	25.2	29.3	25.3
<b>Ga</b>	23	15.4	23.1	22.7	21.5	17.4	16.5	15	13.2	21.3	18.2	20	19.6	22.8	210.3	13.5	14.2	18.2	21.1	20.6
<b>Pb</b>	5.6	3.2	2.6	6.1	4.2	2.3	4.2	2.1	2.6	3.8	4.2	4.1	6.2	3.1	5.7	7.5	4.4	2.3	1.6	5.2
<b>Ti/Y</b>	322.9	298.2	459.4	373.6	424.3	513.1	297.3	441.9	399.7	399.67	785.65	365.32	316.65	413.1	302.23	438.37	264.05	407.16	361.77	582.96
<b>Ti/Zr</b>	61.42	75.94	75.79	55.46	70.06	49.47	47.40	62.78	65.10	58.97	98.32	76.41	74.62	68.51	66.49	54.63	91.65	88.84	61.20	64.53
<b>Zr/Ti</b>	0.016	0.013	0.013	0.018	0.014	0.020	0.021	0.015	0.015	0.017	0.010	0.013	0.013	0.014	0.015	0.018	0.011	0.011	0.016	0.015
<b>Zr/Y</b>	5.26	3.93	6.06	6.74	6.06	10.37	6.27	7.04	6.14	6.78	7.99	4.78	4.24	6.03	4.55	8.02	2.88	4.58	5.91	9.03
<b>Zr/Nb</b>	19.40	13.39	25.93	15.44	13.33	17.70	17.59	14.21	9.87	10.89	13.16	8.55	17.23	22.68	12.69	19.33	5.12	12.22	15.79	23.19
<b>Nb/Y</b>	0.27	0.29	0.23	0.44	0.45	0.59	0.36	0.50	0.62	0.62	0.61	0.56	0.25	0.27	0.36	0.42	0.56	0.38	0.37	0.39
<b>Y/Nb</b>	3.69	3.41	4.28	2.29	2.20	1.71	2.80	2.02	1.61	1.61	1.65	1.79	4.06	3.76	2.79	2.41	1.78	2.67	2.67	2.57
<b>Nb/La</b>	0.71	0.85	-	0.60	0.79	-	0.53	0.88	0.74	0.83	-	-	0.71	0.61	0.79	0.99	-	-	0.56	0.87

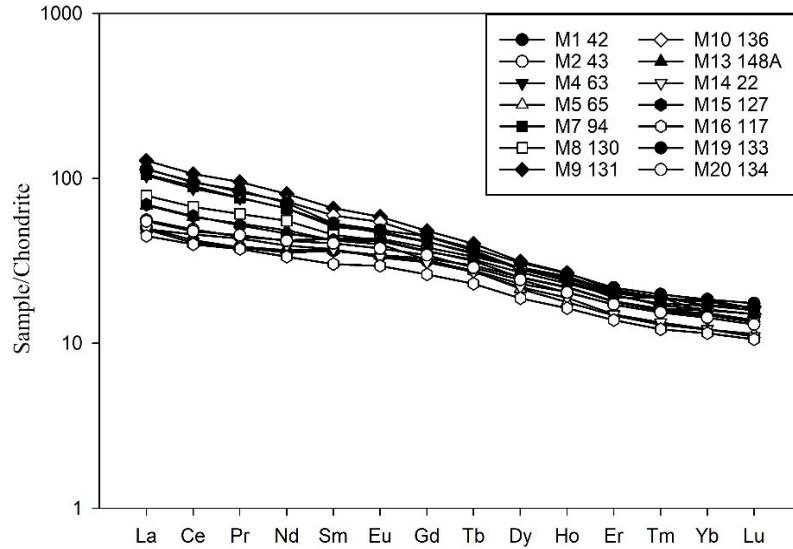
**Table 3.** Geochemical abundance of mafic rocks (rare earth elements in ppm)

Sample Nos.	M1 42	M2 43	M3 44	M4 63	M5 65	M6 93	M7 94	M8 130	M9 131	M10 136	M11 122	M12 126	M13 148A	M14 22	M15 127	M16 117	M17 139	M18 146	M19 133	M20 134
<b>La</b>	11.85	13.25	-	24.68	16.28	-	25.09	18.65	30.4	26.9	-	-	11.62	11.67	16.46	10.61	-	-	27.09	13
<b>Ce</b>	25.9	30.1	-	53.27	35.76	-	55.12	41.22	65.28	58.76	-	-	24.91	28.04	36.3	24.44	-	-	58	29.31
<b>Pr</b>	3.54	4.12	-	7.07	4.939	-	7.1	5.66	8.84	7.67	-	-	3.58	4.01	4.82	3.47	-	-	7.87	4.2
<b>Nd</b>	16.26	19.28	-	30.01	22.14	-	30.01	25.35	36.78	33.14	-	-	16.77	17.9	21.18	15.32	-	-	32.44	19.13
<b>Sm</b>	5.39	6.35	-	7.83	6.24	-	7.56	6.73	9.78	8.82	-	-	5.43	5.51	6.27	4.48	-	-	7.9	5.98
<b>Eu</b>	1.91	2.43	-	2.63	2.25	-	2.69	2.37	3.3	3.07	-	-	1.93	1.87	2.35	1.66	-	-	2.74	2.12
<b>Gd</b>	6.28	7.59	-	8.21	6.38	-	8.24	7.24	9.57	8.83	-	-	6.52	6.17	7.17	5.21	-	-	8.88	6.82
<b>Tb</b>	1	1.21	-	1.28	0.991	-	1.26	1.14	1.45	1.32	-	-	1.07	0.98	1.16	0.83	-	-	1.36	1.04
<b>Dy</b>	5.64	7.114	-	6.91	5.266	-	6.96	6.17	7.73	7.01	-	-	6.21	5.39	6.64	4.61	-	-	7.58	5.97
<b>Ho</b>	1.12	1.39	-	1.31	0.97	-	1.35	1.19	1.46	1.3	-	-	1.2	1.03	1.26	0.89	-	-	1.45	1.11
<b>Er</b>	2.74	3.31	-	3.02	2.36	-	3.23	2.85	3.38	3.16	-	-	2.88	2.39	3.11	2.21	-	-	3.48	2.75
<b>Tm</b>	0.38	0.46	-	0.47	0.32	-	0.46	0.39	0.47	0.42	-	-	0.4	0.33	0.43	0.3	-	-	0.49	0.38
<b>Yb</b>	2.39	2.95	-	2.45	1.95	-	2.88	2.45	2.72	2.58	-	-	2.55	1.96	2.72	1.85	-	-	2.97	2.3
<b>Lu</b>	0.33	0.4	-	0.34	0.28	-	0.4	0.34	0.41	0.37	-	-	0.37	0.27	0.39	0.26	-	-	0.43	0.32
<b>Total</b>	<b>84.73</b>	<b>99.95</b>	-	<b>149.48</b>	<b>106.13</b>	-	<b>152.35</b>	<b>121.75</b>	<b>181.57</b>	<b>163.35</b>	-	-	<b>85.44</b>	<b>87.52</b>	<b>110.26</b>	<b>76.14</b>	-	-	<b>162.68</b>	<b>94.43</b>
<b>(La/Yb)<sub>N</sub></b>	3.37	3.05	-	6.84	5.67	-	5.92	5.17	7.59	7.08	-	-	3.10	4.04	4.11	3.90	-	-	6.20	3.84
<b>Sm/Yb</b>	2.26	2.15	-	3.20	3.20	-	2.63	2.75	3.60	3.42	-	-	2.13	2.81	2.31	2.42	-	-	2.66	2.60
<b>(La/Sm)<sub>N</sub></b>	1.37	1.30	-	1.97	1.63	-	2.07	1.73	1.94	1.90	-	-	1.34	1.32	1.64	1.48	-	-	2.14	1.36
<b>(Ce/Nd)<sub>N</sub></b>	1.19	1.16	-	1.32	1.20	-	1.37	1.21	1.32	1.32	-	-	1.11	1.17	1.28	1.19	-	-	1.33	1.14
<b>(Gd/Yb)<sub>N</sub></b>	2.13	2.08	-	2.71	2.65	-	2.31	2.39	2.85	2.77	-	-	2.07	2.55	2.13	2.28	-	-	2.42	2.40
<b>Eu/Eu*</b>	1.00	1.07	-	1.00	1.09	-	1.04	1.03	1.04	1.06	-	-	0.99	0.98	1.07	1.05	-	-	1.00	1.01



**Fig. 4** Ti/Y vs. Sm/Yb

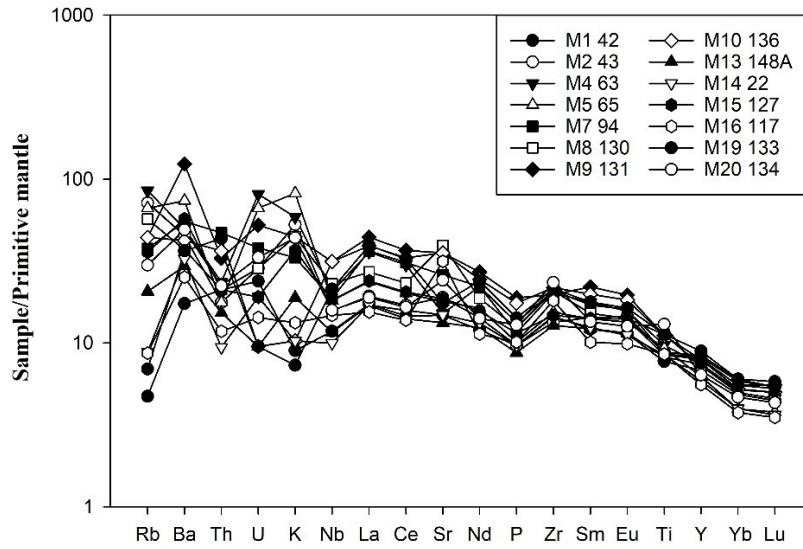
Xu et al. (2001) divided mafic volcanics into two magma types of high-Ti ( $Ti/Y > 500$ ) and low-Ti ( $Ti/Y < 500$ ). Based on this criterion the samples plot in the Ti/Y vs Sm/Yb (degree of HREE fractionation) (Fig. 4). It has been reported that the high-Ti lavas were generated at a lower degree of partial melting, whereas low-Ti lavas could be related to higher degrees of partial melting (Xu et al. 2001). Thus, these samples display a spatial chemical variation from the dominant low Ti lavas to minor high-Ti lavas; suggesting that the high-Ti lavas were generated with lower degree of partial melting than those of low-Ti lavas. Only one sample lies in high Ti basaltic plot (sample M20 134).



**Fig.5** Chondritic normalized REE plot

These volcanic rocks show identical REE patterns with enriched LREE and the slightly depleted HREE pattern with insignificant Eu anomalies (Fig.5). The tholeiitic samples show lesser content of REE ( $\Sigma$ REE=76.14-181.57). The Eu anomaly of all the collected samples have almost same range of values. This insignificant Eu anomaly, samples such as M13 148A and M14 22 show 0.98 and 0.99 respectively while other samples show values slightly more than 1, suggests that plagioclase fractionation played minimum role during their crystallization processes. REE patterns of tholeiitic basalts are relatively moderately steep ( $Ce/Yb)_N$  (2.57-6.3).

The REE patterns of tholeiitic basalts are sub-parallel to one another, indicating fractionation of REE in relatively constant proportions over a significant range of composition. The enrichment in LREE in the present samples can be produced by melting of an enriched LREE mantle source, by crystal fractionation or by assimilation of continental crust (Moraes et al. 2003). These basic rocks have smooth REE and coherent multielemental patterns of HFSEs indicating the incompatible trace elements and REEs are less affected and may reflect primary chemical characteristics of these rocks. The linear trend of incompatible elements like Zr, Nb, P suggests that they may be cogenetic in nature.



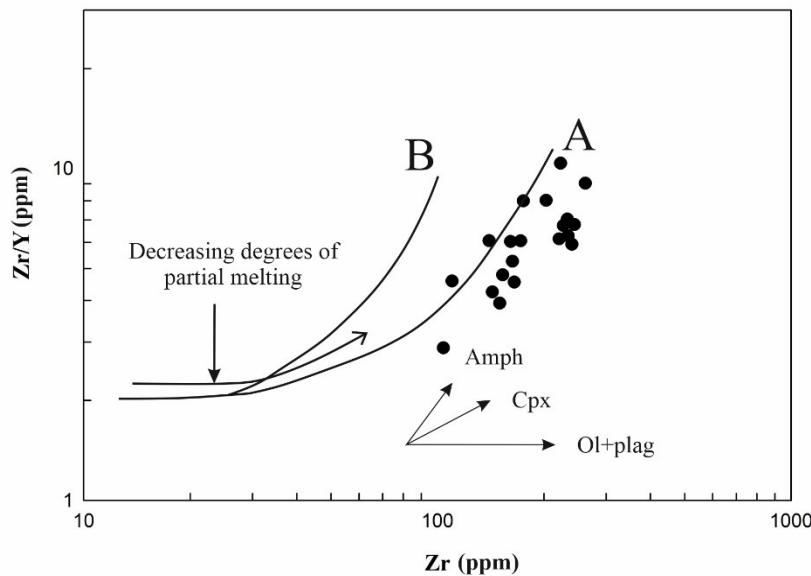
**Fig.6** Primitive Mantle normalized elements pattern

The primitive mantle normalized elements pattern are shown in Fig.6. The primitive mantle normalized elements pattern is based on abundance of a range of incompatible elements normalized to estimates of their abundance in primitive mantle. It's arranged in order of increasing compatibility during melting of mantle. Really basalts from different tectonic settings have different patterns on these normalization diagrams. From this spider plot diagram it's evident that Large ion lithophile elements (such as K, Rb, Th, Ba and Sr) exhibit haphazard behavior. However, these rocks are characterized by a general enrichment from less incompatible to more incompatible elements with negative anomalies of Nb, P, Ti and enrichment in LREEs which are characteristics of many continental types of basalt (Storey et al. 1992). The general enrichment of more incompatible elements relative to less incompatible elements together with negative anomalies for Nb, P, Ti, and the enrichment in LREE relative to HREE is consistent with emplacement in a continental rift environment (Thompson et al., 1983; Mohamed et al., 2000;). These features are common to the primitive mantle normalized trace element profiles of the mafic volcanics suggested that they were emplaced in such an environment.

## CHAPTER THREE

### 3. PETROGENESIS

The incompatible trace elements abundances in the mafic volcanics have been used to constrain their source characteristics. The mafic volcanics have low Zr/Nb (5.12-25.93), Y/Nb (1.61-4.28), Ti/Zr (47.40-98.32) ratios and high Zr/Y (2.88-10.37) ratio reflecting their derivation from enriched mantle source (Le Roex et al., 1983).



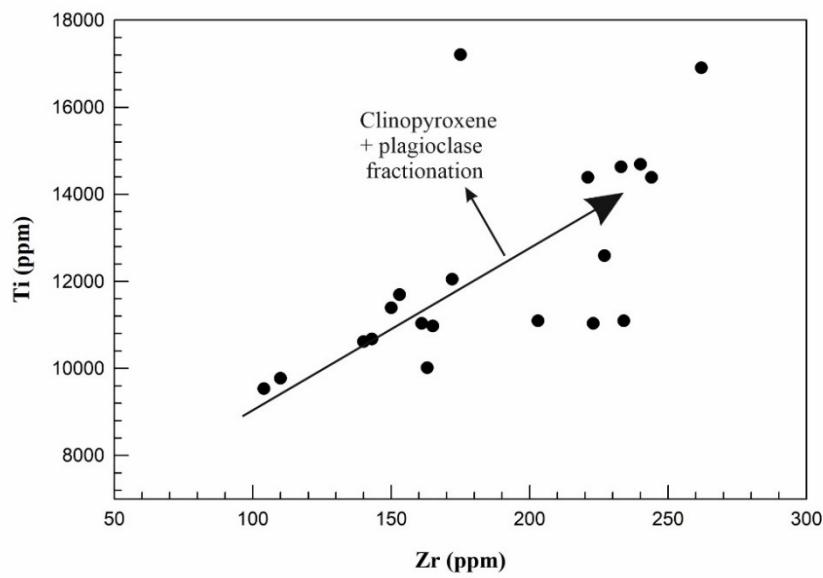
**Fig.7** Zr vs. Zr/Y plot

Two calculated partial melting curves as 'A' (60% olivine + 20% Opx + 10% cpx + 10% Plagioclase) and 'B' (60% olivine + 20% Opx + 10% cpx + 10% garnet) for Achaean mantle sources are shown for comparison with the mafic rocks in the binary plot of Zr vs. Zr/Y (Fig. 7). These rocks closely follow curve 'A' indicating moderate degrees of partial melting of a garnet free mantle source. The combination of low Ti/Y with Zr/Y in these rocks is not consistent with mantle processes involving garnet.

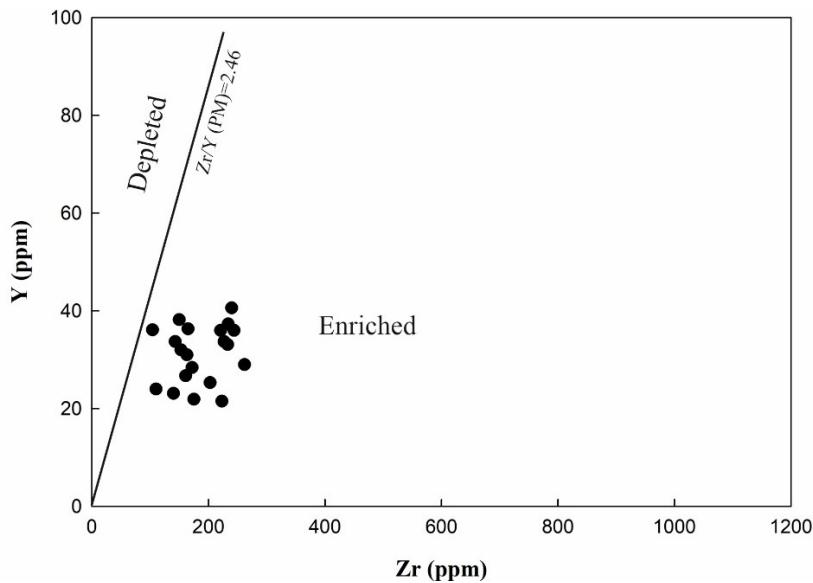
Furthermore, the absence of any HREE fractionation in the REE patterns of these mafic volcanics, indicates that garnet was not present in the source. Thus, garnet may not be present as a residual phase during the genesis of these mafic rocks. In the binary plot (Fig. 7), samples show variation in Zr/Y ratios with increasing Zr abundances, indicating

clinopyroxene with minor amphibole fractionation. Whereas in the Zr vs. Ti plot (Fig. 8), samples show increasing Ti trend with Zr, indicating clinopyroxene and plagioclase as crystallization phases (James et al., 1987). Clinopyroxene fractional crystallization is also indicated by the negative correlation between SiO<sub>2</sub> and CaO, Fe<sub>2</sub>O<sub>3</sub> and Zr, Sc (Table 1 and 2).

Values of highly incompatible trace element ratios such as Nb/La and Ce/Nd normally change very little with moderate degrees of fractional crystallization and are expected to reflect the source characteristics (Saunders et al. 1988). However these ratios may be fractionated to some extent by extremely low degrees of partial melting or due to compositional heterogeneities, in the source region (Ahmad & Tarney 1991). Thus, the narrow variation of Nb/La (0.53-0.99) and (Ce/Nd)<sub>N</sub> (1.11-1.37) ratios in these rocks suggest they are derived from similar sources.



**Fig.8** Zr vs. Ti plot

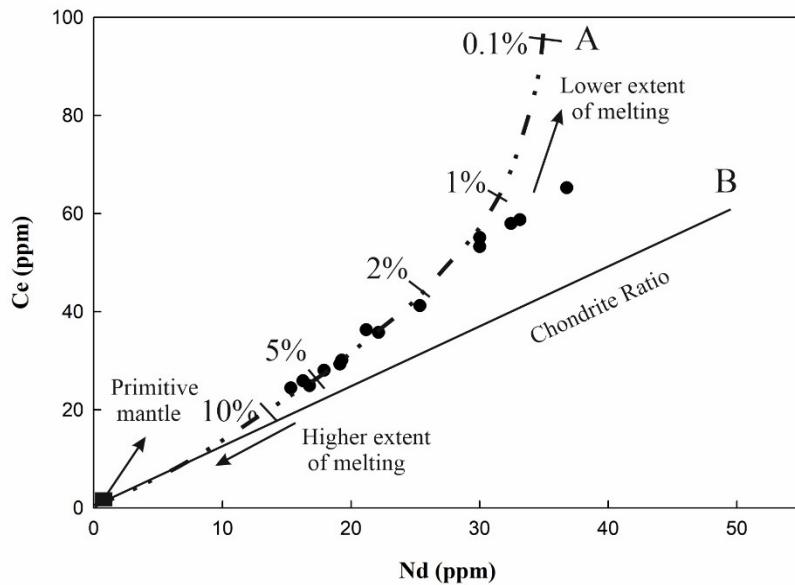


**Fig.9** Zr vs. Y plot

It is well established that geochemical data on volcanics rocks help to interpret source composition, effects of crustal contamination and the tectonic environment of emplacement. Both the tholeiitic and alkaline rocks of this region have low Zr/Nb (5.12-25.93), Y/Nb (1.61-4.28), Ti/Zr (47.40-98.32) ratios and high Zr/Y (2.88-10.37) ratio reflecting enriched nature of these basic volcanic rocks. High MgO content, Ni and Cr in the rocks, indicates that it is compositionally close to its mantle source. The abundance of LILE in magma is controlled by fluid influx, whereas the abundance of the incompatible trace elements including heavy REE (HREE) and HFSEs (Nb, Th, Zr, Y, Ti) are controlled by partial melting processes and mantle depletion (Keppler 1996). Enrichment of incompatible trace elements in the source of these volcanics is indicated by the Zr-Y relationship (Fig.9).

Jenner et al. (1993) have demonstrated garnet has a high partition coefficient for Y ( $D_{\text{garnet/melt}} = 4-11$ ) relative to Zr ( $D_{\text{garnet/melt}} = 0.4-0.7$ ). As varying amount of residual garnet in the sources would change the Y contents in the magmas and Zr/Y would correlate with Y. These volcanic rocks show positive correlation of Zr/Y ratios with Zr contents, but not Y contents. This indicates that there is no residual garnet with Nb/Yb ratios. The negative Nb anomalies in the samples support the mantle source (Hollings & Kerrich 2004). Both the highly compatible elements Cr and Ni show strongly positive

correlations with Mg# (Table 1). These observations suggest that these samples are generally related to each other and probably derived from similar parental magmas. Since a correlation of Nb/Th with Nb/Yb would be expected in the case of mixing between MORB and OIB source mantle. The Nb/Th ratios of these volcanic rocks do not correlate with Nb/Yb ratios indicating significant role of OIB in the source can be ruled out. In the Ti/Y vs Rb/Ba plot, these rocks show large variation of Ti/Y ratio suggests they are not genetically related to MORB and OIB.



**Fig.10** Nd vs. Ce plot

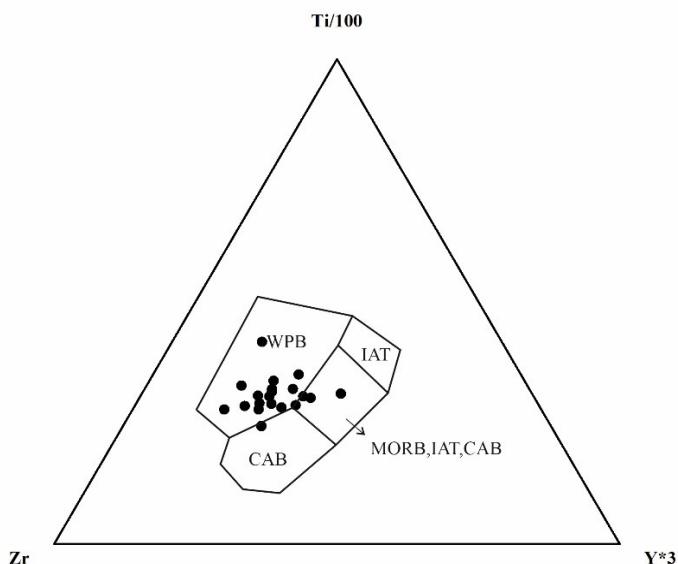
The Ce and Nd relationship is used to evaluate the contamination/assimilation hypothesis. In the Nd vs. Ce plot (Fig. 10) curve A connects points representing varying degrees of partial melting of a primitive mantle source and Ce/Nd ratio of chondrite is presented by line B (Sun and McDonough, 1989). Liquids derived from a mantle derived melt which had suffered progressive crustal contamination or which had undergone combined assimilation fractional crystallisation would instead lie along lines intersecting the Nd axis, not the origin. The mafic volcanics mostly plot along the line intersecting the origin and also along the line of curve A between 1% and 10% partial melting, but above the chondritic line (Fig. 10). This melting range is consistent with limits of tholeiitic magma

generation. The relationship does not support significant effect of crustal contamination on the chemistry of these rocks. The absence of any significant evidence for crustal contamination suggests their ascent through a thin continental crust that was undergoing extension.

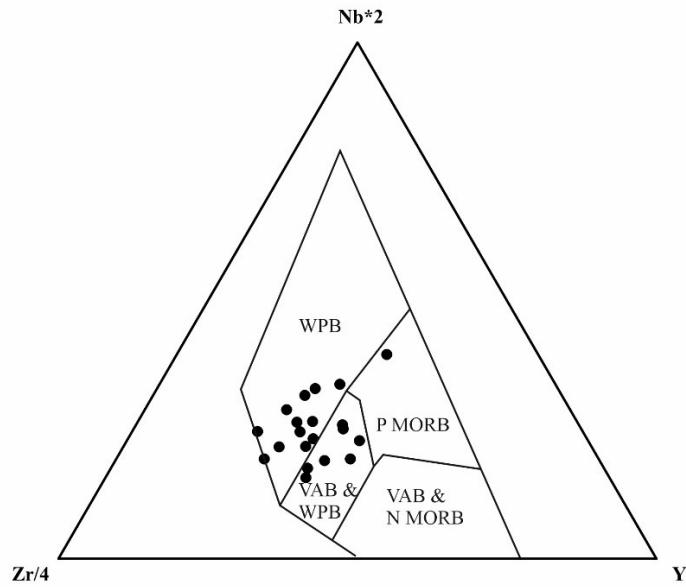
## CHAPTER FOUR

### 4. TECTONIC SETTING

Zr-Ti/100-Y\*3 diagram is used to determine the tectonic setting to which the collected samples fall to, like within plate basalt, island arc tholeiite, continental arc basalt and mid oceanic ridge basalt by using the presence of Ti, Zr and Y elemental content. On the basis of Zr-Ti/100-Y\*3 diagram (Fig. 11), geochemical characteristics of within plate basalt (WPB) is determined for all the samples except two samples which fall in MORB field. Majority of samples are plotted in WPB field on Nb\*2-Zr/4-Y diagram (Fig. 12).

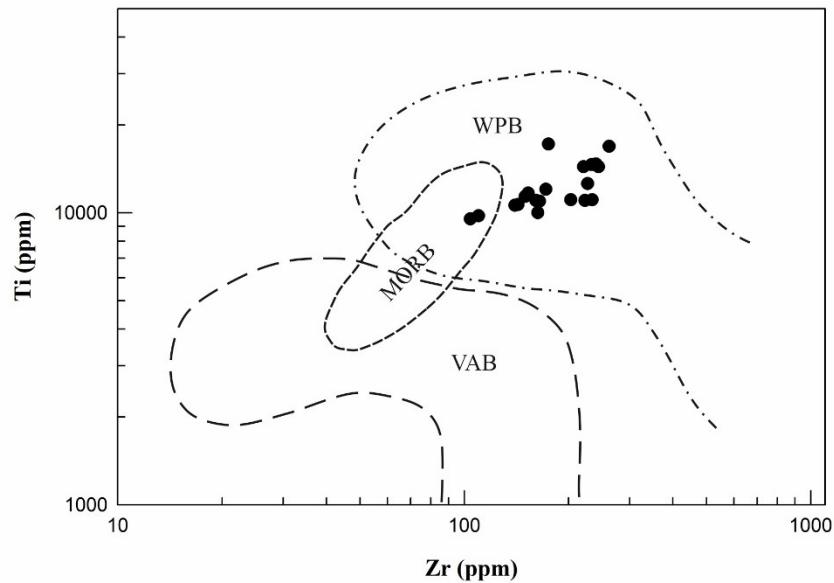


**Fig.11** Zr-Ti/100-Y\*3 plot

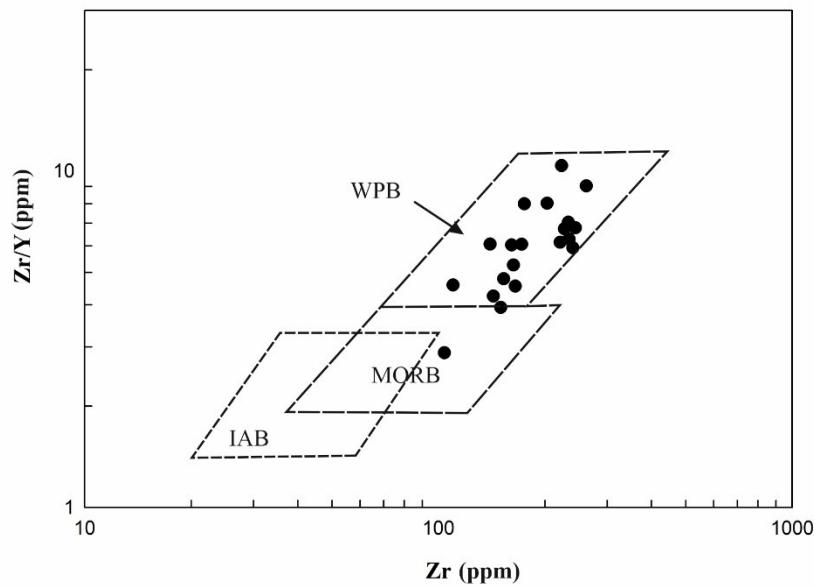


**Fig.12** Zr/4-Y-Nb\*2 plot

Ti vs Zr plot (Pearce 1982) (Fig. 13) reveals strong signature of the 'within plate basalt' of these rocks. Similarly the plot of Zr-Zr/Y (Fig. 14) also decipher that the source of these rocks are of within plate basalt.



**Fig.13** Zr vs. Ti plot



**Fig.14** Zr vs. Zr/Y plot

## **CHAPTER FIVE**

### **5. CONCLUSIONS**

- The samples collected from the study area are predominantly of tholeiitic basalt and two samples are of calc-alkaline.
- Samples are mostly basalt and basaltic andesite.
- The tholeiitic basalt is characterised by enrichment of large ion lithophile elements (LILE), light rare earth elements (LREE), depleted in high field strength elements (HFSE) and fractionated nature along with insignificant Eu anomaly.
- Similarity they are also characterized with low-Ti basalt ( $Ti/Y < 500$ ).
- Their geochemical and petrogenetic studies reveal that they have been generated from enriched mantle source.
- The tectonic setting of the area reveals that the samples are of within plate basalt.

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