CHAPTER - V
PETROCHEMISTRY OF BASALT FLOWS

Stratigraphy and Geochemistry

Introduction

Stratigraphy also called “Historical Geology” is a science dealing with history of rocks of the Earth’s crust with special emphasis on their formations and changes they have undergone since their occurrence. It involves study of layers or strata lying one above the other sequentially. Thus stratigraphy is study of stratified rocks and their sequential arrangement with respect to their time of formation, distribution and Lithological composition.

Deccan Traps were broadly classified in to three groups as Lower, Middle and Upper Traps, based on distribution and relative proportion of inter trappean sedimentary beds at different levels (Krishnan 1960). The lower division comprises Eastern part of the province, Middle division comprises Central Deccan and Malwa plateau and Western Ghats around the Maharashtra and Gujrat covers Upper division.

In the study area i.e. along Chikhaldara Ghat section, 16 Lava flows have been identified on the basis of their field characters. The lava flows of the Ghat section can be distinguished with the help of their stratigraphic position, textural parameters, like Aphyric, Microphyric and Porphyritic nature. Phenocryst assemblages like Plagioclase, Clinopyroxene and Olivine mostly altered to iddingsite, opaque mineral and primary glass. The present stratigraphic divisions mainly based on field characters, phenocryst assemblages, and significant shifts in elemental abundance and ratios mainly K_2O, MgO, TiO_2, P_2O_5, Ba, Sr, Ni, Cr, Zr, Ba/Ti, Ba/Sr, Ba/Zr, Sr/Ti, Zr/Ti, La/Nb, and TiO_2/P_2O_5. Based on the above characteristics, the formations of Chikhaldara exposed along the study area have been further subdivided in to various chemical types (CT), each of which consists of one or more flows showing similar chemical characteristics.

Cox and Hawkesworth (1984, 1985); Bodas et.al. (1985, 1986); Beane et.al. (1986); Davey Lightfoot (1986); and Khadri et.al. (1986, 1996) have provided a comprehensive stratigraphy (12 formations comprising 3 sub groups)
of the Western Deccan Basalt province based on the field, geochemical, petrographic and paleomagnetic investigations (Table No. 5.1). The northern part of western ghat exposes oldest part of lava pile (Kalsubai Sub group) while younger sub group were exposed towards south. The Kalsubai sub group consists of five formations namely Jawahar (oldest), Igatpuri, Neral, Thakurwadi and Bhimashankar (youngest). The Lonawala subgroup divided into Khandala and Bhuse formations whereas the Wai sub group is made up of Poladpur, Ambenali, Mahabaleshwar, Panhala and Desur formation (Beane et. al. 1989).

In this study attempt has been made to divide 492 m thick Deccan Trap Lava pile exposed along Chikhaldara Ghat section into 16 flows. It is hoped that these results may provide a model to bring out regional evolution and structure of Deccan Traps as a whole.

Table 5.1: Stratigraphic Nomenclature and thickness of Western Deccan Basalt formations (Beane et al, 1983, 1986; Cox and Hawksworth, 1984; Lightfoot, 1985, Khadri et.al., 1989)

<table>
<thead>
<tr>
<th>Sub group</th>
<th>Formation(Max.Thickness)</th>
<th>Member or Chemical Type</th>
<th>(87Sr/86 Sr/T)</th>
<th>AvM# TiO2 %</th>
<th>Avg Ba/Zr</th>
<th>Av Zr/Nb</th>
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<td>Desur(&lt;100m)</td>
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<td>48</td>
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For identifying individual lava flows and grouping them into recognizable stratigraphic units, the nomenclature described by Bodas et.al. (1988) and Khadri et.al. (1988) which form a part of National Science foundation (USA) sponsored research project. Western Deccan Traps is being followed in this study. The important lithographic units adopted in this area include group, sub group, formation and flow that are in accordance with classification of international sub commission on stratigraphic terminology.

**Group**: It is major lithostratigraphic unit which embraces two or more continuous or associated formations with significant Lithological features, in common (i.e. The Deccan Basalt group)

**Sub group**: A group can be divided into various sub groups which constitutes formally differentiated assemblage of formations (i.e. Kalsubai, Lonawala sub groups).

**Formation**: A capable sequence of lava showing similar field, petrographic and gross chemical and isotopic features has been termed as formation, which is fundamental unit of Lithostratigraphic classification.
The formation boundaries can be marked by presence of distinct breaks in field appearance or marker horizons (Black, Red and Green boles) which are traceable over a large area with same stratigraphic level associated with considerable shift in chemical trend from the adjacent flows. Marker horizons are not only identified by their lateral traceability but also by physiographic expression and lithological homogeneity. Practicability of mapping and of delineation on cross section is an important consideration in the establishment of formations. Whenever possible the formations are separated into lower, middle and upper divisions (i.e. Thakurwadi formation)

**Member:**

The formal lithostratigraphic unit next in rank to the formation and is always part of the formation is known as a member. It designates a flow or sequence of flows occurring in the same stratigraphic level, having similar physical and chemical characters. However the flows with similar chemical signatures, but occurring at different stratigraphic levels are considered as different members. A member is designated by Geographic name followed by word “member” whereas lithological designation is useful it should be included (i.e. Phyric member of Chikhaldara formation)

**Flow:**

Flow represents smallest unit in lithostatigraphic classification, which is lithologically distinguishable from the overlying and underlying layers. A flow can be either compound or simple. Each compound flow consists of numerous flow units. There are many times pipe amygdales in the form of inverted ‘y’ at the base of flow unit and ropy structure at the top (Walker 1972). Simple flows are thick, horizontal and free from vesicles and amygdales except for small portion at the top, and major lower portions of these flows are jointed.

**Chemical type:**

A flow or sequence of flows occurring at different stratigraphic levels having similar chemical characters within a formation is known as chemical type (CT). Each CT is characterized by its own set of megascopic, microscopic and chemical parameters. Useful chemical parameters are the concentrations of TiO₂,
MgO, Co, P₂O₅, B, Sr, Ca, Ni, Y, Ba/Y, Ba/Ti, Ba/Zr, TiO₂/P₂O₅, Ba/Sr, Zr/Y, Sr/Y and Mg* number etc. Each chemical type exhibits a lesser range of variation within it than between other chemical types (Reidel, 1983).

The result indicates presence of two types in the study area which represent significant change in geochemical signatures. They are

CT-1: Fine grained Aphyric flows.
CT-2: Medium grained Plagioclase phryic flows.

**FLOW STRATIGRAPHY:**

Detailed geological mapping of the lava flows on the basis of field traverses along with Petrographic and Geochemical investigations led to the identification of 492 m thick lava pile made up of 16 lava flows.

**Stratigraphy of Chikhaldara formation:**

Thickness of the Exposed Chikhaldara formation is 492 m this formation consists of 16 flows, out of which seven flows are fine grained Aphyric, seven flows are medium grained Plagioclase phryic, one flow is of Amygdaloidal Basalt (Compound Flow) and one flow is of Volcanic Breccia. The results of Petrographic and Geochemical studies confirm the proposed field stratigraphy. On the basis of Geochemical parameters the flows occurring in this area can be grouped into two chemical types. CT1 and CT2.

**CHEMICAL TYPE CT-1:**

Petrographically this CT is characterized by fine grained Aphyric compact massive flow. This CT is overlying CT2 of same formation. The CT-1 can be distinguished from CT-2 formation due to low percentage of plagioclase and high proportion of olivine. Chemically it shows compositional range of MgO (4.12 to 6.45), TiO₂ (1.83 to 3.67), P₂O₅ (0.13 to 0.29), and CaO (9.05 to 12.06)

**CHEMICAL TYPE CT-2**

Petrographically this CT is characterized by presence of medium grained plagioclase phryic flows. This is occurring below the CT-1. CT-2 can be distinguished from CT-1 due to high percentage of Plagioclase than CT-1 and low proportion of olivine. Chemically it shows compositional range of MgO (4.60 to 5.00), TiO₂ (2.64 to 3.50), P₂O₅ (0.18 to 0.22) and CaO (8.0 to 10.74)
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<th>Sub group</th>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Flow</th>
<th>Characteristic Features</th>
<th>CT</th>
<th>Phenocryst</th>
<th>Gr. size</th>
<th>Geochemistry</th>
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<td>Fine-grained aphyric, compact, massive basalt with microphenocryst of pl.</td>
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<td>x</td>
<td>x</td>
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<td>14 XIV</td>
<td></td>
<td>Fine-grained aphyric, compact, massive basalt.</td>
<td>CT1</td>
<td>x</td>
<td>x</td>
<td>F 4.88 2.64 0.24 224 182 47</td>
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<tr>
<td></td>
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<td>40 XII</td>
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<td>Fine-grained aphyric, compact, massive basalt with microphenocryst of pl.</td>
<td>CT1</td>
<td>x</td>
<td>x</td>
<td>F 6.11 1.83 0.13 210 130 47</td>
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<td></td>
<td>18 XI</td>
<td></td>
<td>Compact massive medium grained aphyric</td>
<td>CT1</td>
<td>x</td>
<td>x</td>
<td>M 6.81 2.08 0.13 219 184 51</td>
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<td>40 X</td>
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<td>Compact massive medium grained aphyric With microphenocryst of Plagioclase</td>
<td>CT1</td>
<td>x</td>
<td>x</td>
<td>M 5.35 2.55 0.20 214 147 49</td>
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<td>Pl Cpx Ol</td>
<td>Mgo TiO₂ P₂O₅ Sr Zr Y</td>
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<td>x x -</td>
<td>F 4.64 2.86 0.22 282 123 36</td>
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<td>30 VIII</td>
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<td>CT2</td>
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<td>Fine grained</td>
<td>CT2</td>
<td>x x -</td>
<td>F 4.64 2.86 0.22 283 124 37</td>
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<tr>
<td>12 V</td>
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<td>Fine-grained aphyric,</td>
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<td>Basalt with microphenocryst of pl.</td>
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<td>25 IV</td>
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<td>Fine grained</td>
<td>CT2</td>
<td>x x -</td>
<td>F 4.60 3.50 0.20 266 253 32</td>
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<td>Compact plagioclase</td>
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<td>23 III</td>
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<td>Compact phryic Basalt</td>
<td>CT2</td>
<td>x x -</td>
<td>M 5.00 2.64 0.18 276 242 35</td>
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<td>with medium sized pl.</td>
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<td>phenocryst</td>
<td></td>
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</tr>
<tr>
<td>47 I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Compact phryic Basalt</td>
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<td></td>
<td>with medium sized pl.</td>
<td></td>
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<tr>
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(96)
Table 5. 3: Representative Chemical Analysis of Stratigraphic formations exposed in the study area

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<th>FORMATION</th>
<th>CHIKHALDARA</th>
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<tr>
<td></td>
<td>CT</td>
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<tr>
<td>MgO</td>
<td>4.12 to 6.45</td>
</tr>
<tr>
<td>CaO</td>
<td>9.05 to 12.06</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.83 to 3.67</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.13 to 0.29</td>
</tr>
<tr>
<td>Ba / (ppm)</td>
<td>208 to 242</td>
</tr>
<tr>
<td>Cr</td>
<td>145 to 189</td>
</tr>
<tr>
<td>Ni</td>
<td>71 to 94</td>
</tr>
<tr>
<td>Sc</td>
<td>22 to 29</td>
</tr>
<tr>
<td>Sr</td>
<td>210 to 224</td>
</tr>
<tr>
<td>Zr</td>
<td>124 to 198</td>
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<tr>
<td>Ba/Y</td>
<td>4.33 to 5.90</td>
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Table 5. 4 Comparison of Geochemical criteria used to define various chemical types

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<tr>
<td>Chemical Type</td>
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<tr>
<td></td>
<td>(Flow Nos. 5,10,11,12,14,15,16)</td>
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<tr>
<td>SiO₂%</td>
<td>47.99 -51 43</td>
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<tr>
<td>Al₂O₃</td>
<td>12.17-15.51</td>
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<tr>
<td>Fe₂O₃</td>
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<td>MgO</td>
<td>4.12-6.81</td>
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<td>----------</td>
</tr>
<tr>
<td>CaO</td>
<td>9.05-12.06</td>
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<td>Na$_2$O</td>
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<td>K$_2$O</td>
<td>0.12-0.53</td>
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<tr>
<td>TiO$_2$</td>
<td>1.83-3.67</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.13-0.29</td>
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<tr>
<td>MnO</td>
<td>0.18-0.24</td>
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<tr>
<td>Ba(ppm)</td>
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<tr>
<td>Co</td>
<td>41-52</td>
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<tr>
<td>Cr</td>
<td>145-189</td>
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<tr>
<td>Cu</td>
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<tr>
<td>Li</td>
<td>7-11</td>
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<tr>
<td>Ni</td>
<td>71-94</td>
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<tr>
<td>Sc</td>
<td>27-29</td>
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<td>Sr</td>
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<td>Zn</td>
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<td>Zr</td>
<td>124-198</td>
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<tr>
<td>La</td>
<td>20-35</td>
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<tr>
<td>Ce</td>
<td>31-59</td>
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<td>Nd</td>
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<tr>
<td>Sm</td>
<td>6.6-9.4</td>
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<tr>
<td>Eu</td>
<td>3.2-4.5</td>
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GEOCHEMISTRY AND PETROGENESIS

Introduction:

The term “Geochemistry” was first used by German-Swiss chemist Christian Freidrich Schonbein in 1838. It is a tool of Chemistry used to solve problems related to Geology and to understand the Earth and it’s working. Geochemistry flourished during second half of the twentieth century and resulted in to greater advancements in understanding our planet. Much of what we know about the Earth and solar system is only due to lot of research on the chemistry of meteorites.

The Geochemical analysis plays important role in understanding nature of the parent magma, its crystallization history and genesis of rocks. Geochemical variation of rock is useful in identification, classification and nomenclature whose mineral constituents cannot be easily determined due to minute size. In addition

<table>
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<tr>
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<th>7.3-10.4</th>
<th>4.7-9.12</th>
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<tr>
<td>Dy</td>
<td>4.2-5.9</td>
<td>3.1-4.10</td>
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<td>Yb</td>
<td>113.66-65.94</td>
<td>104.16-82.57</td>
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<tr>
<td>Ba/TiO₂</td>
<td>0.99-1.08</td>
<td>1.03-1.02</td>
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<tr>
<td>Ba/Sr</td>
<td>1.67-1.22</td>
<td>2.22-1.14</td>
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<td>Ba/Zr</td>
<td>114.75-61.03</td>
<td>100.76-80.85</td>
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<td>Sr/TiO₂</td>
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<td>Zr/TiO₂</td>
<td>14.07-12.65</td>
<td>14.66-15.91</td>
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<td>TiO₂/P₂O₅</td>
<td>0.041-0.071</td>
<td>0.08-0.09</td>
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<tr>
<td>TiO₂/Y</td>
<td>2.82-3.88</td>
<td>3.87-6.66</td>
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<tr>
<td>Zr/Y</td>
<td>4.73-4.74</td>
<td>8.59-7.60</td>
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<tr>
<td>Ba/Y</td>
<td>4.77-4.39</td>
<td>8.31-7.45</td>
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to this, chemical analysis is helpful in working out stratigraphic correlation of different formations.

In the study area although there is significant compositional variation observed in some of the flows but majority of the flows is showing much uniformity in their chemical composition. In case of such flows which look similar in their megascopic and microscopic characters Trace and Rare Earth Elements analysis has played important role in distinguishing them.

During this study Chemical analysis of representative samples has been carried out and their detailed petrochemical characteristics and crystallization behavior were discussed for various major, trace and rare earth elements with the help of binary and ternary diagrams. In this study attempt has been made to understand various petrogenetic processes involved during emplacement and environment of crystallization through the chemical analysis and interpretation of behavior of various chemical elements and their ratios with comparison of geochemical criteria used to determine various chemical types (Table 5.4)

**Previous Geochemical work on the Deccan Trap:**

Vemban (1947) grouped available analysis of the Deccan Trap to determine the differentiation trend in the basalts. Sukeshwasla and Poldervaart (1958) have given 73 chemical analyses of the Deccan Trap rocks mostly from the Mumbai region. West (1958) and Chaterjee (1964) have given the chemical analysis of rocks from Saurashtra and Pawagad areas respectively. Karkare (1965), has worked out the major and minor oxides of lower middle and upper traps

Large numbers of papers dealing with Geochemistry of the Deccan traps are published in Geochemistry section of special issue of Bulletin Vulcanologique (1972). Marathe (1976) has determined nature of magma type of the flows and dykes occurring in Nasik area with the help of Chemical analyses of basalts and associated dykes in Pune area to ascertain nature of parent magma and to delineate petrogenetic history.
Large number of papers dealing with geochemistry of Deccan traps and related basalt provinces are published in geological society of India Memoir No. 3 by Subbarao and Sukeshwala 1981.

Beani et.al. (1986) has shown that the Basalts of Western ghat exhibit considerable variation in their Magnesia content. Chande (1987) has worked on major oxides of the dykes occurring in Aurangabad and Jalna districts of Maharashtra. The Chemical analysis of dykes in Wadgao-Talegao area by Ghosh (1987) show variation in distribution of major and minor oxides. Powar et.al. (1989) with the help of analysis of major oxides of basalt flows in Deccan Plateau, indicated an interplate tectonic set, only for Deccan volcanic. R. Durai swami (1994) on the basis of chemical studies concluded that the basalt flows and associated dykes show close correspondence in their mineralogy and Chemistry. Nair et.al (1996) have done the work on Geochemistry of rocks occurring in Western Satpura region. A.V. Tejankar (2002) has carried out Chemical Analyses of 13 Basalt Flows and 5 Basaltic Dykes occurring between R. L. 348 m and 1135 m of Toranmal Ghat Section Dist. Nandurbar

**Geochemical variation and Petrogenesis of lava flows:**

**Variation in major oxides:**

From the Table No. 5. 8 given below, it can be seen that the flows are having silica% in between Tholeiites and Olivine Basalts. Average Silica % values arranged in increasing order are Olivine Basalt (47.16%), Aphyric Flows (49.17%), Phyric Flows (49.47%) and Tholeiitic Basalts (51.03%)

All these values are trending towards average value of tholeiites, which is 51.03%.

Al$_2$O$_3$ % values of Phyric flows are lower than that of Aphyric flows and are nearing to Olivine Basalts. The average Al$_2$O$_3$ % arranged in increasing order are Tholeiite-13.66%, Phyric Flows 13.75%, Olivine Basalt 13.76% and Aphyric Flows 13.92%.

Fe$_2$O$_3$ % values of Phyric Flows and Aphyric Flows are much higher than that of average values of Olivine Basalts and Tholeiite Basalts. The average Fe$_2$O$_3$ value of flows is 15.53%
Very high % of Fe₂O₃ in phryic and aphyric flows is indicative of either prevalence of oxidizing conditions at the time of formation of flows or the presence of water in the magma in large proportion than normal amounts. However H₂O% which is not included in the chemical analysis due to LOI, precipitates FeO as Magnetite after converting it to Ferric state rather than formation of ferrous silicates such as Fayalite (Goldschmidt 1954) Tiwari (1972, p. 1144) has given values of Fe₂O₃ : FeO for Pawagadh basalts as 9.74 : 9.74 and 9.12 : 5.92 Similarly Diwakar Rao et.al (1972 p. 1160) reported higher values of Fe₂O₃ from 4.78% to 8.75% for Tandur Basalts in Andhra Pradesh. Also Krishna Murthy (1972 p. 935) reported higher values of Fe₂O₃ from 3% to 8.40 % of dyke rocks of Rajpipala hills, Gujrat. According to him it may be due either to the invariable alteration of the olivine as well as some of the oxides or because of high oxygen pressure of the magma as suggested by Osborn (1959) which may be due to high original water content of the magma.

Average MgO% of flows (5.12%) is slightly less than that of Tholeiite (5.18%) but is much less than that of Olivine Basalt (9.73%). MgO% values arranged in increasing order are Phryic Flows (4.69%), Tholeiite (5.18%), Aphyric Flows (5.56%) and Olivine Basalt (9.73%).

Average CaO% of flows (10.35%) is more than that of tholeiite and Olivine Basalt. CaO% arranged in increasing order are Tholeiite (9.83%), Phryic Flows (9.96%), Olivine Basalt (10.15%), Aphyric Flows (10.74%).

Na₂O% in flows is less than that of Olivine Basalt and Tholeiite. Average Na₂O% arranged in increasing order are, Aphyric Flows (2.19%), Phryic Flows (2.37%), Olivine Basalt (2.54%) and Tholeiite (2.74%).

K₂O% of flows is less than that of Tholeiite and Olivine Basalt. Average K₂O % arranged in increasing order are Aphyric Flows (0.23%), Phryic Flows (0.57%), Tholeiite (0.79 %) and Olivine Basalt (0.80%).

Average TiO₂ % of flows (2.76%) is nearer to that of Olivine Basalt (2. 72 %) but is much more than that of Tholeiite (2.23%). The average TiO₂% arranged in increasing order are Tholeiite (2.23%), Aphyric Flows (2.6 %), Olivine Basalt (2.72%), Phryic Flows (2.92%).
There is some variation in $P_2O_5$ %. Average $P_2O_5$% arranged in increasing order are- Aphyric Flows (0.19%), Phyric Flows (0.21%), Olivine Basalt (0.29%), Tholeiite (0.32%).

There is very less variation in MnO%. Average MnO% values arranged in increasing order are- Olivine Basalt (0.12%), Tholeiite (0.17%), Aphyric flows and Phyric flows (0.2%).

These results can be grouped as follows

<table>
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<tr>
<th>TYPE</th>
<th>Maximum Percentage of</th>
<th>Minimum Percentage of</th>
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<td>Phyric Flows</td>
<td>Fe$_2$O$_3$, TiO$_2$, MnO</td>
<td>MgO</td>
</tr>
<tr>
<td>Aphyric Flows</td>
<td>Al$_2$O$_3$, CaO, MnO</td>
<td>Na$_2$O, K$_2$O, P$_2$O$_5$</td>
</tr>
<tr>
<td>Olivine Basalt</td>
<td>MgO, K$_2$O</td>
<td>SiO$_2$, MnO</td>
</tr>
<tr>
<td>Tholeiite</td>
<td>SiO$_2$, Na$_2$O, P$_2$O$_5$</td>
<td>Al$_2$O$_3$, CaO, Fe$_2$O$_3$, TiO$_2$</td>
</tr>
</tbody>
</table>

Between Tholeiite and Olivine Basalts Tholeiite is rich in SiO$_2$, Na$_2$O, P$_2$O$_5$ while Olivine Basalt is rich in MgO, K$_2$O. An attempt has been made to find out geochemical behavior of the flows in the area studied by using different methods.

The chemical variation of different lava flows exposed in the study area has been studied with the help of certain major, trace and rare earth elements and their ratios (Fig. 5.1 to 5.4). It has been observed that there is negligible chemical variation within a flow; however certain flows indicate enrichment of certain elements in their middle portion as compared to top and bottom portion of the flow. The chemical proportions of various elements (major, trace and REE) supplements already established stratigraphy.
Fig. 5.1: Chemical variation diagram against height for study area
Fig. 5.2: Chemical variation diagram against height for study area
Fig. 5.3: Chemical variation diagram against height for study area
Fig 5.4: Chemical variation diagram against height for study area
Major element Geochemistry:-

Alkali Silica variation:

Kuno’s variation diagram (1965) which was later modified by Sugisaki and Tanaka (1971) indicate that the Basalts in study area can be grouped in to high potash and low potash Tholiiites with few samples showing Alkali basalt field. This Silica Vs Alkali variation diagram indicates Tholeiitic nature of lava flows with few lie in Alkali field. This result indicates no clear differentiation trend of fractional crystallization. (Fig. 5.5)

Variation of MgO Vs all Oxides

The plotting of MgO Vs all major elements shows their relative abundance and their relative trends. As MgO decreases continuously during fractional crystallization of mafic liquids irrespective of their primitive composition. The variation of MgO Vs SiO$_2$ indicates scattered nature without any trend. However Al$_2$O$_3$, CaO and to some extent MnO show positive correlation with MgO, whereas Fe$_2$O$_3$, TiO$_2$, K$_2$O show negative trend which can be attributed to fractionation of plagioclase and clinopyroxene with traces of olivine (Fig. 5. 6).

The MgO vs. TiO$_2$ show lower concentration of TiO$_2$ and higher concentration of MgO for CT-1 due to the presence of

Aphyric flows showing least evolved nature. However the Plagioclase phytic flows show high TiO$_2$ and low MgO indicating the evolved nature (Fig.5.6).
Fig 5.5: Variation of Na$_2$O+K$_2$O Vs SiO$_2$ Indicating Tholeiitic nature of Basalt with fractional crystallization trend
Fig 5.6: Variation of MgO Vs. all Oxides
Fig. 5.6 (a): Variation of MgO Vs all Oxides
Table 5. 5 Representative Geochemical analysis of Basalt flows exposed in Chikhaldara ghat section

<table>
<thead>
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TABLE NO. 5.6: Chemical analysis of Plagioclase Phyric Flows
(Major Elements)

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<tr>
<td>MgO</td>
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<tr>
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</tr>
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<td>MnO</td>
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Table No. 5. 7: Chemical analysis of Aphyric Flows (Major elements)

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<td>4.12 5.35 6.81 6.11 4.88 5.18 6.45 5.56</td>
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<tr>
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<tr>
<td>K2O</td>
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<tr>
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<tr>
<td>Total</td>
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</table>
The average composition of Phyric flows and Aphyric flows have been worked out. The average values of the flows have been compared with the average chemical analyses of the Deccan trap tholeiites and Olivine Basalts after Marathe (1976) who has found out average of four analyses of Deccan trap Tholeiites and 5 analyses of Olivine Basalts along with analyses carried out by different workers in different areas these values are given in table No. 5.8.

Table No. 5.8: Recalculated values of the flow types

<table>
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<th>Average of Phyric and Aphyric</th>
<th>Olivine Basalts</th>
<th>D. T Tholeiites</th>
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**TiO₂ Vs MgO, P₂O₅, K₂O and CaO/TiO₂ variation**

The dominance of fractional crystallization is shown by negative correlation in TiO₂ Vs MgO plots, whereas P₂O₅ and K₂O show positive correlation with least enrichment of P₂O₅ and TiO₂ for aphyric flows and high values for Plagioclase phyric flows indicate highly evolved nature without much time gap between them.

The variation of incompatible elements (TiO₂) have been used in relation to CaO/TiO₂ to understand the nature of primary liquid and degree of partial melting which shows negative correlation suggesting the dominance of fractional crystallization process with minor amount of partial melting process. A strong correlation to the MORB values is noticed. The ratio increases as TiO₂ decreases thereby indicating progressively release of Ca from mantle source. (Fig. 5.7)
(FeO/MgO) Vs SiO$_2$, FeO, MgO; Al$_2$O$_3$/SiO$_2$ Vs MgO and Al$_2$O$_3$ Vs CaO and alkali index variation

The variation of FeO/MgO Vs SiO$_2$ and FeO indicate positive correlation and negative correlation with MgO showing increase in MgO indicating that these rocks are fairly contaminated than the other flows (Fig. 5.8). This is in support of the view that basaltic magma is generally controlled by assimilation followed by crystal fractionation and the most fractionated magmas will also be most contaminated (Campbell and Gorton, 1980; Beane et. al., 1986; Khadri, 1989) This ratio can either be indicator of the extent of fractional crystallization of olivine and clinopyroxene or the composition of mantle source with which the parent magma is in equilibrium (Mahony, 1984).

The Al$_2$O$_3$/SiO$_2$ Vs MgO variation show positive correlation indicating the decrease of fractional crystallization process from plagioclase phyric to aphyric flows. This is supported by lower concentration for the least evolved one.

**Harker variation diagram:**

SiO$_2$ Vs major element variation diagram show limited range of these elements with lot of variation in Silica content. Most of the oxides except Fe$_2$O$_3$ show negative correlation with Silica. The Al$_2$O$_3$ variation shows role of plagioclase in fractionation. (Fig. 5.9)

**P$_2$O$_5$ Vs major element variation:**

The variation of P$_2$O$_5$ with all major oxides show positive correlation with Na$_2$O, K$_2$O, and TiO$_2$ which indicates that the Plagioclase Phyric Flows have been evolved progressively whereas Aphyric flows have been least evolved. The similar behavior has been reported from other parts of Deccan (Chatterjee, 1970; Mahony et. al., 1983, Sreenivasa Rao et. al., 1985; Khadri 1989, the Karoo volcanic of South Africa Cox, 1983), Volcanics from Gregary rift of Kenya (Baker et. al. 1977), Kolumbia river basalts (Hooper et. al. 1984). MgO and Al$_2$O$_3$ show negative correlation with P$_2$O$_5$ indicating progressive evolution of lava flows (Fig. 5.10)
Fig 5. 7: Variation of TiO$_2$ Vs MgO, P$_2$O$_5$, K$_2$O and CaO/TiO$_2$
Fig. 5. Variation of Fe$_2$O$_3$/MgO Vs SiO$_2$, MgO, Fe$_2$O$_3$
Fig. 5.8 (a): Variation of SiO$_2$ Vs Zr/TiO$_2$, Al$_2$O$_3$ Vs CaO, Na$_2$O vs. K$_2$O
Fig. 5.9: Harker Variation diagram
Fig. 5.9 (a): Harker Variation diagram
Fig. 5. 9(b) : Harker Variation diagram
Fig. 5.9 (c): Harker Variation diagram
Fig. 5.9 (d): Harker Variation diagram
Fig. 5.10: P2O5 Vs Major element variation diagram
Fig. 5. 10 (a): P2O5 Vs Major element variation diagram
Felsic and Mafic index:

i) Felsic Index (F. I)

Simpson (1954 p 238) proposed the term felsic index, which is ratio

\[
\frac{(Na_2O+K_2O) \times 100}{CaO+Na_2O+K_2O}
\]

(Values in wt %). This provides convenient index of the degree of fractionation of the felsic minerals which constitutes Bowens Continuous reaction series.

Felsic index values arranged in increasing order are Aphyric Flows 18, Phyric Flows 23 and Olivine Basalt 24. 76 and Tholeiite 26. 42.

ii) Mafic Index (M. I):

The mafic group corresponds to Bowen’s discontinuous reaction series. The ratio

\[
\frac{(FeO+Fe_2O_3) \times 100}{MgO+FeO+Fe_2O_3}
\]

(Values in wt %) which was devised by Wager and Deer (1939) is used as an index of mafic fractionation and is designated by Simpson (1954 p 238) as mafic Index.

Mafic Index values arranged in increasing order are Olivine Basalt 55. 73, Aphyric Flows 56. 0, Tholeiite 72. 37, and Phyric Flows 77. 0.

The variation of felsic index \([\{Na_2O+K_2O\}/\{CaO+Na_2O+K_2O\}]\) and mafic index \([\{FeO+Fe_2O_3\}/\{FeO+Fe_2O_3+MgO\}]\) Vs TiO_2, P_2O_5, Ba and Zr were plotted to understand magmatic differentiation processes by following the nomenclature given by Simpson (1954). The result indicates positive trend for TiO_2, P_2O_5 and Zr. The Plagioclase Phyric flows show higher values of Felsic index (Ave 0. 23) as compared to that of Aphyric flows (Ave 0. 18). As per as Mafic Index is concerned Plagioclase Phyric Flows show higher values (Av 0. 77) as compared to that of Aphyric Flows (Av. 0. 56). Such higher values of Felsic and Mafic indices of Plagioclase Phyric flows are indication of their evolved nature. (Fig. 5. 11)
Fig. 5. 11: Variation of Felsic Index Vs. TiO$_2$, P$_2$O$_5$, Ba, Zr
Fig. 5.11 (a) : Variation of Mafic Index Vs TiO$_2$, P$_2$O$_5$, Ba, Zr
Fig. 5.11 (b) Variation of Felsic Index Vs. Mafic Index
Solidification Index:

Kuno (1959) has proposed solidification index S. I which is represented as:

\[
S. I = \frac{\text{MgO} \times 100}{\text{MgO} + \text{FeO} + \text{Na}_2\text{O} + \text{K}_2\text{O}}
\]

According to him S. I decreases during the fractionation of most igneous series and would therefore afford a more reliable measure of fractionation of Basalt. Magma than SiO₂ %. This was established in pigeonitic rock series of Japan and Skaergaard intrusion.

According to Kuno (1962) magma of primary origin i.e. undifferentiated rocks have S. I values between 35 to 40 and those produced by fractionation in the middle stage are near about 25. However certain Picrite Basalts and Olivine Basalts pose some difficulties, which are having S. I values higher than 40. According to Kuno these are products of accumulation of olivine crystals.

S. I values for the rocks in the area studied when arranged in increasing order are Phyric Flows - 20. 00, Tholeiite- 23. 25, Aphyric Flows-25. 00, Olivine Basalts- 38. 43. Most of the tholeiitic rocks occurring in India are having S. I values about 25(Chatterjee, A. C., 1972 p. 1045) However the olivine basalts have greater values of S. I Coats (1968, p. 698, 700, 704) stated the values of olivine basalt as 31. 0 to 36. 4. Similarly, Vishwanathan and others (1972 p. 1121) reported the average S. I value for some olivine basalts around Kalyan to be 41. 50. Thus it is observed that S. I values are higher for Olivine Basalts. The lower S. I values of the flows of the area studied is indicative of more affinity towards tholeiitic basalt magma type than olivine basalt.

In this area total 16 flows have been demarcated out of which seven flows are of Compact Phyric Basalts and seven flows are of Compact Aphyric Basalts. One flow is of Amygdaloidal basalt (Compound Flow) and one flow is of Volcanic Breccia. All these flows are resting over each other chronologically. Flow No. 1 is the oldest flow and Flow No. 16 is the youngest one. The total vertical thickness is found to be 492m. i.e. from R. L. 600m to R. L. 1092m. All these flows have been analyzed chemically.
I) Classification of rocks based on S. I. :

Kuno (1968, p646/7) suggested the grouping of rocks according to their S. I., instead of SiO2 content. He suggested following classification.

<table>
<thead>
<tr>
<th>S. I Values</th>
<th>Rock type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 9</td>
<td>Dacite</td>
</tr>
<tr>
<td>10-19</td>
<td>Andesites</td>
</tr>
<tr>
<td>20-29</td>
<td>Basalt andesites</td>
</tr>
<tr>
<td>30-39</td>
<td>Basalt</td>
</tr>
</tbody>
</table>

Thus Flow nos. 1, 3, 6, 7, 8, 9, 10, 14, 15 and 16 can be grouped as Basalt Andesite and Flow nos. 4, 5 are Andesites, in which S. I values are tending towards Basalt Andesites and only Flow nos. 11, 12 can be grouped as Basalts.

This method is given by Kuno (1957), where in S. I. =\([100 \times \text{Mgo}] / \{\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O}\}\]. The variation diagram have been plotted for S. I. Vs CaO, K\(_2\)O, TiO\(_2\), P\(_2\)O\(_5\) and also Vs trace elements like Ba, Y, Zr, La and Nd. Kuno showed that during fractionation of most of the igneous rocks the S. I values decrease steadily and thus provide reliable indication of fractionation. Rock samples of the study area are giving S. I. values in the range of 17.79 to 33.31, which fall in middle stage fractionation of Kuno (1965). The S. I. shows positive correlation with CaO indicating decrease of fractionation from Plagioclase Phyric Flows to Aphyric Flows. The S. I. shows Negative correlation with K\(_2\)O TiO\(_2\), P\(_2\)O\(_5\), Y, Zr, La and Nd indicating differentiation trend showing dominance of fractionation crystallization with an increase in aphyric flows. (Fig. 5.12)
Fig. 5.12 : Variation of Solidification Index with Major elements
Fig. 5.12 (a): Variation of Solidification Index with trace elements
Fig. 5.12 (b) : Variation of Solidification Index with trace elements
Fig. 5.12(c): Variation of Solidification Index with MgO, Sc, Ni
Fig. 5.12(d) : Variation of Solidification Index with trace elements
Ternary Variation diagram:

Wager and Deer (1939) proposed the plotting of F. A. M. diagram. In this diagram points representing Phyrig flows, Aphyric Flows and Tholeiite are close to each other while point representing olivine basalt is away from them. (Fig. 5. 13)

TiO$_2$-K$_2$O-P$_2$O$_5$ discriminate diagram reveals that most of the samples from study area have affinity towards ocean floor basalts with few trending towards continental group (After Pearce, 1983). The results indicate that the basalts from the study area are quartz normative tholeiitic evolved within a plate tectonic setting. The Ti-Zr-Sr and Ti-Zr-Y diagrams have been utilized for discriminating tectonic settings of various basaltic provinces by Pearce and Cann (1973). In Ti-Zr-Y diagram most of the samples in study area are falling in the field of within plate basalts and a few in ocean floor basalts. In Ti-Sr-Zr diagram, most of the plots fall in the field of ocean floor basalts with a few falling in the continental basalt field. This indicates distinct affinity of basalts in the study area towards oceanic environment. The slightly higher concentration of TiO$_2$ in the study area when compared to average tholeiites might be responsible for their tendency towards oceanic environment. Similar results have been reported from other parts of Deccan Traps (Sreenivas Rao, 1984; Ramasubba reddy1985, Dhandapani, 1988; Khadri, 1989).

Most of the samples of study area form a cluster falling in the tholeitic which is inferred by the [Fe$_2$O$_3$+ TiO$_2$+CaO] - SiO$_2$- Al$_2$O$_3$ (Rochi diagram). The K$_2$O- Na$_2$O- CaO discriminant diagram has been plotted to understand the various tectonic environments of the study area. The results indicate utmost of the basalts fall in to quartz normative tholeiitic field evolved within the plate lactic setting. K$_2$O-MgO- Al$_2$O$_3$ variation diagram reveals that most of the samples fall in continental or ocean ridge floor basalts indicating chemical affinity towards ocean floor (Fig. 5. 13).
Fig 5.13: TiO$_2$-K$_2$O-P$_2$O$_5$ variation Diagram
Fig 5.13 a: Ti-Zr-Sr and Ti-Zr-Y variation Diagram
Fig 5.13 b : K₂O- Na₂O- CaO Variation Diagram
Fig 5.13c: $K_2O-MgO-Al_2O_3$ and $K_2O-MgO-P_2O_5$ Variation Diagram
Trace element Geochemistry:

In terms of changing concentration expressed in ppm, trace element variations are discussed which provide broad framework to understand petrogenetic relationship both within and between the chemical types and formations. The variation pattern of trace elements give clear understanding regarding role of these elements in various petrogenetic processes, like fractional crystallization, partial melting, magma mixing and crystal contamination.

Zr Vs all major and trace elements variation:

To understand partial melting and fractional crystallization process, variation of ‘Zr’ with other elements has been plotted which can be utilized as reliable index of evolution. Zr increases at constant rate regardless of whether olivine, pyroxene or plagioclase is fractionating or in what proportion these phases are added or removed. The variation of Zr with SiO₂, Al₂O₃, Na₂O, K₂O show considerable scatters represented by separate clusters for each formation. On the other hand Fe₂O₃, SiO₂, P₂O₅ show distinct trend indicating fractional crystallization process associated with minor amount of partial melting. The Aphyric flows show low degree of fractionation indicating their less evolved nature. Whereas Plagioclase phyric flows show higher concentration indicating highly evolved nature. The Zr Vs MgO and CaO variation diagram demonstrates distinct variation between the various chemical types.

There is positive correlation of Zr with MgO and negative correlation with both TiO₂ and CaO. The MnO show less variation with Zr. (Fig. 5. 14).

The variation of Zr with Ba, Ni and Cu shows positive correlation, indicating fractionating process with the increase of these elements with Zr indicating evolved nature of Plagioclase phyric flows, however aphyric flows clusters at lower and forming distinct groups due to their less evolved nature. The variation of Cr shows positive correlation. The Aphyric flows show higher concentration of these elements with lower Zr indicating their less evolved nature, whereas plagioclase phyric flows show lower concentration of these elements with Zr. The variation of Sc Vs Zr indicates different tectonic environments present in the study area in relation to chondrites. It also indicates control of mantle mineralogy during process of melting.
The basalts of the study area show higher values when compared with chondrites. These results are supported by similar observations made from other parts of Deccan Traps (Sreenivas Rao, 1984; Dhandapani, 1988; Khadri, 1989 and in Gregory rift volcanic (Baker, et. al.  1977).

The variation of Zr with some trace and rare earth elements indicate the role of fractional crystallization process. It also indicates dominance of these elements in plagioclase flows showing highly evolved nature.

**P₂O₅ Trace element variation:**

Positive correlation is indicated by the variation of P₂O₅ with Ba with higher concentration for highly evolved plagioclase phyric flows and lower concentration for aphyric flows indicating their least evolved nature. The crystal fraction process increases from aphyric flows, whereas Ni, Cu, Cr show negative correlation with P₂O₅ indicating fractionation process with the increase of these elements for highly evolved flows. The aphyric flows show large scatter. (Fig. 5. 15)

A positive correlation is shown by variation of certain trace (Sr, Zr) and REE (La, Ce, Sm) elements with P₂O₅ indicating the role of fractionation process, with the dominance of plagioclase and clinopyroxene associated with minor amount of crustal contamination. This is in support of the view that the basaltic magma is generally controlled by assimilation followed by crystal fractionation and the most fractionated magmas will also be most contaminated ones (Khadri, 1989).

**MgO Vs Trace Element variation:**

To understand relative abundance and the trends, MgO Vs trace elements have been plotted as MgO decreases continuously during fractional crystallization of mafic liquids irrespective of their primitive composition. MgO Vs Cr, Ni show positive correlation indicating fractionation of Plagioclase and Clinopyroxene. Whereas MgO shows negative correlation with Ba, Li, Sr, Zr showing the trend of fractional crystallization of plagioclase which increases from aphyric flows. The variation of Ba, Li and Zr with MgO indicates the trend of Olivine fractionation and V shows positive trend and Sc shows negative trend. (Fig. 5. 16)
Variation of Ba/Zr Vs Cu, Cr, Ni Vs Cr, Ti/Yb Vs Nd:

The variation of Ba/Zr Vs Cu show positive correlation with the use of fractional crystallization process from aphyric to Plagioclase phryic flows. The Ni Vs. Cr shows positive correlation, whereas Ti/Yb Vs Nd shows negative correlation. The variation from aphyric to phryic flows indicate a trend showing enriched mantle source. (Fig. 5. 17)

Sr Vs Ba/Zr, Zr/Y, Ba/Y and Nd variation:

The variation of Sr Vs Ba/Zr and Sr Vs Nd indicate negative correlation whereas Sr Vs. Ba/Y and Zr/Y indicate considerable positive correlation, suggesting dominance of fractional crystallization process with an increasing trend from least evolved aphyric to evolved phryic flows. (Fig. 5. 18)

Fe/(Fe+Mg) Vs Cr/(Cr+Al) Variation

Fe/(Fe+Mg) Vs Cr/(Cr+Al) have been plotted to understand the nature of enrichment pattern for these elements in the upper mantle. In general scattered nature of these elements indicates dominance of fractional crystallization process.

Y/Zr Vs Ba/Zr and P2O5/TiO2 variation:

The variation of Y/Zr Vs Ba/Zr has been plotted to understand distinctness of various chemical types exposed in study area in relation with considerable shift in their trends. Similarly P2O5 /TiO2 Vs Ba/Zr diagram also show positive correlation confirming dominance of fractional crystallization process. In general aphyric flows show higher concentration of both these elements indicating less evolved nature of these flows whereas Plagioclase phryic flows show lower values of these elements indicating highly evolved nature. (Fig. 5. 19)
Fig 5.14: Zr Vs Major, Trace and REE variation diagram
Fig. 5. 14(a) : Zr Vs Trace and REE variation diagram
Fig. 5. 14(b): Zr Vs REE and Major elements variation diagram
Fig.5. 14(c) : Zr Vs Trace and Major elements variation diagram
Fig. 5. 14(d): Zr Vs REE, Major and Trace elements variation diagram
Fig 5. 14 (e) : Zr Vs Major, REE and Trace elements variation diagram
Fig 5.14(f): Zr Vs Trace elements and REE variation diagram
Fig 5.15: P2O5 Vs Trace element and REE Variation Diagram
Fig 5. 15(a) : P2O5 Vs Trace element and REE Variation Diagram
Fig 5.15(b) : P2O5 Vs REE and Trace element Variation Diagram
Fig 5. 15(c) : P2O5 Vs Trace and REE Variation Diagram
Fig. 5. 15 (d): P$_2$O$_5$ Vs Trace element Variation Diagram
Fig. 5.16: Variation of MgO Vs Trace element variation diagram
Fig. 5.16(a): Variation of MgO Vs Trace element variation diagram
Fig. 5.16 (b): Variation of MgO Vs Trace and REE variation diagram
Fig. 5.16 (c): Variation of MgO Vs REE variation diagram
Fig 5.16(d): Variation of MgO Vs REE and Trace element variation diagram
Fig. 5.17: Ba/Zr Vs Cr, Cu and Ni Vs Cr variation diagram
Fig. 5.18: Sr Vs Ba/Zr, Zr/Y, Ba/Y and Nd variation diagram
Fig. 5.19: Y/Zr Vs Ba/Zr and P$_2$O$_5$/TiO$_2$ Vs Ba/Zr variation diagram
Rare Earth element Geochemistry:

The rare earth element pattern plotted for various elements in the study area reveal that fractional crystallization was quite dominant process during the cooling, in general all the chondrite normalized pattern show LREE enrichment, low and nearly flat HREE pattern indicating predominance of fractional crystallization. The results of experimental petrology indicate that tholeiitic basalts might have been fomed by about 15 to 30% melting of the upper mantle peridotite (Green and RingWood, 1968) thus large variations in LREE patterns of tholeiitic lava flows exposed in the study area can be attributed to the variation in LREE content of the mantle source. The fractional crystallization of Plagioclase, Clinopyroxene, and Olivine from tholeiitic basalts do not result in much change in their REE content unless the degree of crystallization is large Khadri, 1989). The rocks exposed in the study area show minute negative anomalies for Eu indicating absence of plagioclase in fractionation process. (Fig. 5. 20, 5. 21). The REE pattern for various chemical types belonging different formations have plotted which indicate the dominance of fractional crystallization process. The aphyric flows show less abundance of REE due to their less evolved nature whereas Plagioclase phyrlic flows show enrichment of REE indicating high degree of fractionation and evolved nature (Fig. 5. 20).

In general overall enrichment of REE in various formations exposed in the study area indicates somewhat similar trend irrespective of their stratigraphic position of various chemical types. This can be interpreted as the possible presence of similar enriched source for these rocks.

\[(Ce)^N \text{ Vs } (Ce/Yb)^N \text{ and } Ce \text{ Vs } La, Zr, \text{ variation:}\]

These variations are positively correlated. Their results are similar to the trends obtained Harburgite-Lherrolite suits from different locations. The results obtained in study area indicate predominance of fractional crystallization associated with minor amount of partial melting.
**Variation of CaO Vs. (La/Sm)\textsubscript{N} and (La/Yb)\textsubscript{N}; (La/Sm)\textsubscript{N} Vs (La/Ytb)\textsubscript{N}; Yb Vs. La/Sm:**

The variation of CaO Vs. (La/Sm)\textsubscript{N} indicates considerable scatter with indistinct positive correlation of these elements. However (La/Yb)\textsubscript{N} values show negative correlation with CaO indicating role of crustal contamination. (La/Sm)\textsubscript{N} Vs (La/Yb)\textsubscript{N} variation diagram shows positive correlation with increase of fractional crystallization process. Yb Vs. La/Sm variation plot shows positive correlation.

**P\textsubscript{2}O\textsubscript{5}/Y Vs. TiO\textsubscript{2}/Y and Zr/Y Variations:**

The variation of P\textsubscript{2}O\textsubscript{5}/Y Vs. TiO\textsubscript{2}/Y and Zr/Y diagram have been plotted to understand nature of fractionation process along with enrichment of these elements with minor scatter showing dominance of fractional crystallization process with minor amount of partial melting which increases from aphyric to plagioclase phyrich flows. (Fig. 5. 22)
Fig 5.20: (Ce) N Vs (Ce/Yb) N, Ce Vs La and Zr variation diagram
Fig 5.21: CaO Vs (La/Sm)N, (La/Yb)N and (La/Sm)N Vs (La/Yb)N and Yb Vs La/Sm variation diagram
Fig 5.22: $P_2O_5/Y$ Vs $TiO_2/Y$ and $Zr/Y$ variation diagram
MORB NORMALISED TRACE ELEMENTS ENRICHMENT PATTERN

To understand nature of enrichment and process of contamination, MORB normalized trace element variation patterns have been studied by making use of methodology given by Cox and Hawkesworth (1984) who have demonstrated that contamination of magma, particularly with granitic material must be enriched in these elements relative to the uncontaminated lavas. These results have considerable similarity in the trend with the variation in enrichment pattern. The phyric flows show more enrichment of Ba content. The enrichment of incompatible elements increases from aphyric to plagioclase phyric flows indicating intermediate stages.

PETROGENETIC MODELLING OF LAVA FLOWS:

The mineralogical and geochemical data plays important role in identification of various petrogenetic processes. In addition to its aid in mapping and correlating the flow sequences and establishing the flow stratigraphy. Most of the mineralogical and chemical variations observed in the study area can be accounted for by the dominance of crystal fractionation associated by a minor degree of crystal contamination, accumulation and partial melting process in varying degrees. During this study an attempt has been made to understand the nature and extent of various petrogenetic processes that could have produced the rocks and to quantify various magmatic processes. In this study major, Trace and Rare Earth Element variation diagrams have been utilized to demonstrate the dominance of fractional crystallization process associated with minor occurrence of crystal contamination, crystal accumulation and partial melting.

Different petrogenetic modes have been proposed by various workers (Beane and Hooper, 1988; Khadri, 1989; Beane et. al., 1986) following computer aided statistical packages containing least square modeling program. Multi component grams related to petrogenesis. In this study an attempt has been made to correlate trends of various major, trace and rare earth element pattern to understand their petrogenetic aspects which are supported by the inverse relationship between Sr$^{87}$/Sr$^{86}$ which are ascribed to the effect of granitic contamination (Beane, et. al., 1986).
Deccan Trap magmas might have been erupted through multiple centers, the most prominent of which may have been a shield volcano–like structure in the western ghat area. The lavas are predominantly tholeiitic, alkali mafic lavas and carbonatites are rare. Radioisotope dating, magnetic chronology and age constraints from paleontology indicate that although the eruption started some 68 Ma, the bulk of lavas erupted at around 65 to 66 Ma. Paleomagnetic constraints indicate an uncertainty of ±500000 years for peak volcanic activity at 65 m.y. in the type section of western ghats. These calculations suggest that the >1.7 km thick Western Ghats section might have erupted within much shorter time interval of ~55000 years, implying phenomenal eruption rates that are orders of magnitude larger than any present day eruption rate from any tectonic environment. Other significant observations/conclusions are as follows. 1) Deccan Lavas can be grouped in to stratigraphic sub divisions based on their geochemistry. 2) While some formations are relatively uncontaminated others are strongly contaminated by continental crust; 3) Deccan Magmas were produced by 15{30% melting of Fe rich tholeiitic source at ~3{2GPa; 4) Parent magmas of relatively uncontaminated Ambenali formation had a primitive composition with 16% MgO, 47% SiO2 5) Deccan Magmas were generated much deeper and by significantly more melting than other continental flood basalts. 6) The erupted Deccan Tholeiitic lavas underwent fractional crystallization and magma mixing at ~ 0.2 GPa. The composition and origin of the crust and crust mantle boundary beneath the Deccan are discussed with respect to influence of Deccan magmatic episode (Gautam Sen., 1995).

A schematic model for the origin of Deccan Traps volcanism by Melting of Lithosphere and Plume

Sheth (2005) suggested presence of large eclogite bodies in the sub continental lithosphere, however instead of a plume, he suggested that these bodies are remnant of ancient subduction; and the Deccan Trap magmas formed when such bodies delaminated from the lithosphere and were heated as the asthenosphere was raised to fill the void. For reasons stated earlier, a plume is necessary. Sheth (2007) pointed out that the Deccan lithosphere was not
significantly uplifted as would be required by the thermal models. In our model melting of large eclogite blocks in the continental craton resulting in the lower lithosphere erosion would offset the buoyancy exerted by the plume. In this connection, the investigation by Kumar et. al. (2007) shows that the Indian lithosphere to be only ~100km thick whereas the once the contiguous Gondwana land lithosphere beneath the other southern continents were 180-300 km thick. These Authors suggested that the plume that severed the Gondwana continents was responsible for melting the lower lithosphere beneath India although they remarked that the role of Deccan plume causing such lithospheric erosion could not be ascertained. In our view, the plume that produced Deccan picrites also melted the eclogite bodies embedded in the lower lithosphere and thereby eroded lower lithosphere. Gautam and Chandrasekharam suggested that a large plume, rising perhaps from the core/mantle boundary, was the primary cause of this flood basalt event. Following Kumar et. al. (2007), it is possible that the pre-Deccan continental lithosphere had an uneven thickness; It was generally 200km. thick beneath cratonic areas and relatively thin (100 km or less) beneath pre-existing rift zones, such as the Cutch and Son-Narmada (SONATA) rift zones. As the Deccan plume came up it melted and eroded much of the lower lithosphere that had inclusions of dispersed blocks of old orogenic eclogite bodies producing contaminate and differentiated appearing tholeiites. Where parts of the plume could rise to shallower levels beneath pre-thinned lithosphere (such as beneath ancient rifts), it produced picritic magmas at ~1550°C and 2. 3GPa, these picrites produced dunite cumulates near moho and gabbroic fractionates in the shallow crust. Our model has components that are similar to hypotheses put forth by “plumsists” and “non plumsists” as well and emphasizes a complex magma production history from the plume as well as ancient continental lithosphere. They have considered magma production volume, rapid eruption, difficulty in explaining the extent of contamination, wide, major and trace element diversity of Deccan Tholeiites, eclogite melting and the requirement of picritic parent magma (therefore an implide peridotite source) in some areas. These considerations are best explained with a model that requires the generation of both picritic magma
from peridotite source and dominant tholeiitic magmas from a mixed source. A mixture of eclogite blocks and surrounding lithospheric peridotite (dominant). Picrite magmas were produced from peridotite source at ~1550°C and >75km. It is difficult to constrain the generation conditions of the magma from eclogite blocks, but given the extent of thermal anomaly, they would have melted entirely as they were heated (Yaxley 2000). The estimated potential temperature of 1550°C would have made DMA significantly hotter than the shallow convecting mantle. This excess temperature, enormous volume of the erupted lavas, short eruption span (the bulk of them erupting in less than 1 million year), age track of Deccan – Laccadives-Maldives-Reunion, and broad isotopic similarity of the “common signature” lavas to those from the reunion hot spot, all favor a plume origin of Deccan Traps with dual source, i.e. eclogite or charnockite and a Fe rich peridotite, the eclogite in our model is a part of continental lithosphere (also in Sheth 2005b) and not recycled subducted oceanic lithosphere brought up by the plume for other geologic areas. (e.g. Campbell 2005). In this sense this model is plume for other geological areas (e.g. Campbell 2005). In this sense this model is similar to that presented by Camp and Hanan (2008) for the Columbia river flood basalts of North Western U. S. A. (Gautam Sen and Chandrasekharam, 2011)