Chapter 5
GEOCHEMISTRY

5.1 INTRODUCTION

Geochemistry is one of the most important tools to understand the involved processes in the evolution of magmatic rocks and has vast applications in earth science studies. After detailed field observation, petrography and mineral chemistry of the mafic dykes, still some processes are yet to be recognized using whole-rock geochemistry. The whole-rock major, trace including rare earth element (REE) geochemical investigations of the mafic dykes from Nainital (ND), Almora (AD) and Pithoragarh (PD) regions have been carried out primarily to infer the processes of the magmatic differentiation such as fractional crystallization, partial melting and crustal contamination during the intrusion of dykes. The geochemical database can also be used to classify the individual rocks, igneous series and to understand the tectonic setting in which the dyke magmas were evolved and emplaced. These databases have also been used to recognize the volcanic series, the tectono-magmatic environment and physical conditions (P-T) of the mafic dyke magma evolution. The geochemistry of the mafic dykes has been compared with Precambrian volcanic rocks of Himalayan to know the relationships of the studied mafic dykes with them, if any, and to decipher the regional geochemical variation geological correlations of the mafic dyke magmas in the Kumaun Lesser Himalaya (KLH).

5.2 SORTING AND PRESENTATION OF THE GEOCHEMICAL DATABASE

Forty-two samples representative of ND, AD and PD from KLH were selected and analysed for whole-rock major and trace including rare earth element (REE) geochemistry using XRF and ICP-MS techniques respectively. The details of the analytical techniques used in the present study were already discussed in the sections 3.3.5 and 3.3.6 of chapter 3. The studied mafic dykes are found partially to moderately affected by Himalayan orogeny thereby showing development of joints in the dyke bodies, particularly noted for PD samples. The samples were thus collected from the margin to the core of the mafic dyke bodies and along the dykes so that the entire bodies could be covered, which can help understanding the geochemical changes from the margin to the core and along the length (strike) of the dykes. The locations of the representative samples are shown in figure 2, and the summarized petrophysical and mineralogical parameters of the mafic dykes are also shown in table 3. The major-oxides and CIPW normative minerals of the ND, AD and PD are given in the tables.
13, 14 and 15 respectively. The analytical results of trace elements and their important ratios of genetic significances are shown in the tables 16, 17 and 18 whereas rare earth elements (REE) are given in the tables 19, 20 and 21 for the ND, AD and PD respectively. The average value and standard deviation of the major, the averages of trace and chondrite-normalized (after Taylor and McLennan, 1985) values of rare earth element (REE) of ND, AD and PD are also given in table 22, 23 and 24 respectively.

For geochemical and petrogenetic studies of the igneous rocks, the primary compositions of the rocks must be clearly ascertained whether the rocks have undergone alteration to some extent by chemical weathering processes or not. Although all possible care have been taken for the selection of samples and processing while treating them for geochemical analysis, the petrographic studies of the mafic dyke rocks of ND, AD and PD show low degree of alteration such as sericitization and hydration by changing anhydrous to hydrous minerals e.g., amphibole and biotite from pyroxenes particularly noted at the margin of the dykes. The degree of alteration in PD is slightly higher than that of ND and AD, but AD show negligible alteration as compared to PD and ND. This is further evident by the observed primary compositions of unaltered mineral grains boundaries. These changes are likely to be produced by secondary processes and may have modified, to a certain extent, the primary chemical compositions of the mafic dykes. There are several parameters to differentiate the primary compositions from secondary ones. The first and foremost step is to examine the results of Loss on Ignition (LOI) of the samples. The altered mafic dyke samples from ND, AD and PD can be deciphered based on elevated values of LOI. Since most of the LOI results of the analysed samples are less than 2.6%, therefore all the results of forty-two samples can be treated primary in nature for geochemical and petrogenetic interpretations. Similarly, the chemical index of alteration (CIA) of the samples can also calculated based on molar Al2O3-(CaO+Na2O)-K2O as (A-CN-K) and molar Al2O3-(CaO+Na2O+K2O)-(FeO+MgO) as (A-CNK-FM) parameters after Nisbett and Young (1984, 1989) in order to examine the degree of chemical changes of the samples. These results can be used to differentiate the primary ND, AD and PD compositions from secondary ones for further genetic interpretations (Figs. 25a, b). The CIA values of all the forty-two samples from ND, AD and PD are less than 50 and are much closed to the unaltered bedrocks basalts and andesite thereby confidently chosen for further geochemical classification, interpretations and recognizing the source and magmatic processes responsible for dyke magma evolution.
5.3 GEOCHEMICAL CLASSIFICATION

The broad classifications of the mafic dykes (ND, AD and PD) have been carried out through petrography, mineral assemblages and mineral chemistry. The ND and PD are leucogabbro to gabbro (sensu strict) in nature whereas AD belongs to gabbro, based on modal mineralogy. The accurate classifications of the mafic dyke rocks based on geochemistry can also be carried out using several schemes. The most commonly used methods for classification are mainly based on whole-rock chemical and normative compositions that have been used widely to classify the basalt types as per the recommendation of International Union of Geological Science (IUGS) Subcommittee on
Systematics of Igneous Rocks (Le Maitre, 2002). According to IUGS scheme, there are several binary and ternary discriminations diagrams which are mainly based on whole-rock major, and trace including the rare earth element (REE) content and their ratios. In the present study, an attempt has been made to understand the basaltic series, tectono-magmatic affiliations and possible tectonic settings in the evolution of mafic dykes using extensive geochemical parameters.

5.3.1 Nomenclature of the mafic dykes

The most useful and commonly referred classification of the volcanic rocks is total alkali vs. silica (TAS) parameters originally suggested by Le Bas et al., (1986) and later adopted by IUGS (Le Maitre, 2002). TAS contents of ND, AD and PD classify them mostly as basalts and a few of PD show affinity with picro-basalts. Some samples from ND and AD also fall in basanite field indicating that the mafic dykes has wide range of compositions largely from tholeiitic (subalkaline) to mildly alkaline (Fig. 26). A slight compositional difference between PD, AD and ND can be observed i.e. PD are alkali depleted as compared to AD and ND. Mildly alkaline nature (basanite: >10% olivine norm) of AD and ND appears caused by slightly elevated alkali content induced either due to low degree of contamination with the country rocks and/or formed by low degree of partial melting of upper mantle rocks.

The ND, AD and PD samples were plotted on SiO₂ vs. K₂O diagram (Le Maitre, 2002) that relates all PD and a few of ND to medium-K basalt whereas AD and ND have shown affinity with high-K basalt series (Fig. 27). The K₂O values of AD and ND are much higher than the PD within the similar range of SiO₂ content.

Based on CIPW normative colour index (CI=ol+opx+cpx+mt+il+hm) and silica content of ND, AD and PD, three different zones for the studied mafic dykes can be observed. ND show typical leucobasalt and AD can be classified as typical basalt. However, PD in between the leucobasalt and basalt and thereby showing transitional zone between ND and AD mafic dykes (Fig. 28). These properties are also supported by the colour index recognized in hand specimens and the petrological properties of ND, AD and PD. Individually, the CI values increase within a narrow range of SiO₂. AD have much higher CI value than that of PD and ND. PD show intermediate between AD and ND. It is therefore suggested that there are much involvement of the ferromagnesian minerals in the evolution of mafic dykes of ND, AD and PD, mostly controlled by fractional differentiation.
Fig. 26 Total alkali vs silica diagram (TAS) of Le Maitre (2002) of ND, AD and PD. Symbols are same as figure 15.

Fig. 27 K$_2$O vs. SiO$_2$ classification of ND, AD and PD after Le Maitre (2002). Symbols are same as figure 15.

Fig. 28 SiO$_2$ vs. C. I (colour index) plot for ND, AD and PD, where (CI=ol+opx+cpx+mt+il+hem), after Streckeisen, 1979. Symbols are same as figure 15.

De La Roche et. al., (1980) has proposed a projection scheme for classification of volcanic rocks based on multicationic $R_1$ vs. $R_2$ factors, where $R_1$=[4Si-11(Na+K)-2(Fe+Ti)]
and $R_2=6[Ca+2Mg+Al]$ factors are primarily derived from Yoder and Tilley (1962) basaltic tetrahedron. The ND, AD and PD samples can be effectively grouped in the field of *gabbro* (silica saturated basalt) but a few of AD in *gabbro norite*. (Fig. 29).

![R1 vs R2 plot for ND, AD and PD classification scheme of De La Roche et. al. (1980). Symbols are same as figure 15.](image)

**Fig. 29** R1 vs R2 plot for ND, AD and PD classification scheme of De La Roche et. al. (1980). Symbols are same as figure 15.

The high field strength element (HFSE) ratios Nb/Y vs. Zr/TiO$_2$ plot, after Winchester and Floyd (1977), of ND, AD and PD reveals nature of samples mostly alkali-basalt except one each sample of ND and PD which show affinities with sub-alkaline basalt and trachy-andesite respectively (Fig. 30). However, Zr/TiO$_2$ vs. SiO$_2$ plot shows affinities of samples with subalkaline to mostly alkaline basalts in nature (Fig. 31). In term of Nb/Y vs. Ti/Y ratio diagram (Floyd and Winchester, 1978; Floyd, et. al., 2000), all samples of ND, AD and PD show tholeiitic metabasites having differential ratios of Ti/V for ND, AD and PD. The Ti/V ratio of PD has shown higher variation from slightly elevated above low-Ti tholeiitic metabasites to more than 1.2 whereas AD and ND have similar range of Ti/V variation. It is also observed that Ti/V ratio of PD, AD and ND (as a group) increases with increasing ratio of Nb/Y (Fig. ).
Fig. 30 Zr/TiO₂ vs Nb/Y ratio plot of ND, AD and PD, after Winchester and Floyd (1977). Symbols are same as figure 15.

Fig. 31 Zr/TiO₂ vs SiO₂ diagram of ND, AD and PD showing the classification (Winchester and Floyd, 1977). Symbols are same as figure 15.

Fig. 32 Ti/V vs Nb/Y plot for ND, AD and PD, the boundary are taken from Floyd and Winchester, 1978; Floyd et. al., 2000. Symbols are same as figure 15.
5.3.2 Identification of the associated basaltic series

The volcanic series of the basaltic rocks can be identified on the basis of major elements compositions. In terms of SiO$_2$ vs. Na$_2$O+K$_2$O diagram (Irvine and Baragar, 1971) of ND, AD and PD, the samples lie on the discrimination boundary between alkali basalt and subalkali (tholeiitic series) basalt (Fig. 33). However, all samples of AD show alkali basalt nature whereas both the ND and PD have shown the affinity with both alkaline and subalkaline basaltic series. These features are equivocally demonstrated by FeO$^\text{f}$/MgO vs. SiO$_2$ plot (after Miyashiro, 1974) of ND, AD and PD (Fig. 34).

![Fig. 33 Total alkali vs. Silica diagram for ND, AD and PD after Baragar (1971). Symbols are same as figure 15.](image)

Based on FeO$^\text{f}$-Na$_2$O+K$_2$O-MgO (AFM) triangular plot of Irvine and Baragar (1971), the samples have affinity with high-Fe tholeiitic series but a few of ND plot in calc-alkaline series (Fig. 35). In FeO$^\text{f}$+TiO$_2$-Al$_2$O$_3$-MgO triangular diagram (Jensen, 1976) for discriminating the major high-Fe tholeiite and high-Mg tholeiite, most of the samples of PD
and ND have indicated high-Mg tholeiite series but a few have shown affinity with high-Fe tholeiite series. Particularly, AD have shown affinity exclusively with high-Mg tholeiite series (Fig. 36).

Fig. 35 AFM diagram after Irvine an Baragar (1971) fo the ND, AD and PD samples. Symbols are same as figure 15.

Fig. 36 Al2O3-(FeO+TiO2)-NgO ternary diagram (after Jensen, 1976 of ND, AD and PD. Symbols are same as figure 15.

5.3.3 Tectono-magmatic environment

The studied mafic dykes are taken from three different tectonic segments according to their locations on the different tectonic units in the Kumaun Lesser Himalaya (KLH). It is therefore likely that mafic dyke magmas may also represent various tectono-magmatic environments depending upon geochemical attributes. The elements which are to be selected for the tectonic discrimination must be immobile during the metamorphism and weathering. Therefore, the HFSE such as Ti, Zr, Nb and Y are considered immobile and commonly preferred for tectonic discrimination since they are immobile and remain intact in the system even during the high degree of chemical weathering and metamorphism (Condie, 1976). In conjunction with the trace elements, some of the major oxides such as P2O5, MnO, FeO and Al2O3 are also used for tectonic discrimination as suggested and used successfully elsewhere. The advantages of using the major-oxides with trace elements are that they can be detected easily and more accurately as compared with the trace elements (Rollinson, 1993). Most of the existing tectonic discrimination diagrams have been developed from the geochemical data of basaltic rocks of known tectonic environments.

The ternary diagram based on TiO2-K2O-P2O5 components of (Pearce et. al., 1975) the studied mafic dykes can be used to distinguish between the oceanic basalt and continental basalt. All the samples of ND, AD and PD plot in the basalt of continental affinity except one
ND which has slightly higher value of TiO₂ and therefore approaches towards oceanic basalt (Fig. 37). The SiO₂ value of the studied samples from ND, AD and PD ranges between 42 and 51 wt.%. According to Pearce et. al., (1977) the ternary FeO-t-MgO-Al₂O₃ plot is useful to discriminate tectonic environment of samples having SiO₂ value between 51 and 56 wt.%. The ND, AD and PD samples plot in mid-ocean ridge basalt (MORB) and a few of ND and PD plot in island arc and active continental margin (Fig. 38), however, the SiO₂ value is observed lesser than that of the suggested limit.

![TiO₂-K₂O-P₂O₅ discrimination ternary diagram of ND, AD and PD, after Pearce et. al., 1975. The line divides the oceanic and continental compositions. Symbols are same as figure 15.](image1)

![FeOt-MgO-Al2O3 diagram plotted for ND, Ad and PD (after Pearce, 1977). Fields are 1-spreading center, 2-island arc and continental active margin, 3- MORB, 4- ocean island basalt and 5- continental basalt.](image2)

Based on Ti-Zr-Y triangular discrimination parameters (Pearce and Cann, 1973), the ND, AD and PD samples exhibit wide data scatter occupying all the tectonic fields. Most of the data even plot beyond the fields, which are unreliable for tectonic discrimination of studied mafic dykes (Fig. 39). Wide scattering of data is due to having relatively higher content of Ti and Y but lower Zr content than the desired values for basalt types. Few ND, AD and PD have shown affinity with calc-alkaline basalt and MORB. The Ti-Zr-Y ternary plot is applicable to the samples having value of CaO+MgO range between 12 and 20wt.% (Rollinson, 1993). The CaO+MgO values of all analysed ND, AD and PD lie within this limit but interestingly could not give the reliable results. These same features were also shown by Ti vs. Zr plot (Pearce and Cann, 1973), where data plotted outside the fields but a few PD and ND plotted within calc-alkaline basalt and MORB (Fig. 40). However, it is suggested that if the tholeiitic basalt has concentration of cumulus Ti bearing minerals such as titanomagnetite and clinopyroxene, this ternary plot is not applicable and therefore cannot give reliable result.
(Rollinson, 1993). This is because of fact that cumulate rocks can never represent primary melt composition, and will reflect the composition of segregated (cumulus) minerals and entrapped post-cumulus phases.

Fig. 39 Ti-zr-Y triangular diagram of ND, AD and PD, Pearce and Cann, 1973. The delineating fields are A-island arc tholeiite, B-MORB, C-calc-alkaline basalt and D-Within plate basalt. Symbols are same as figure 15.

Fig. 40 Ti vs. Zr discrimination diagram for ND, AD and PD after Pearce and Cann (1973). The fields are A- island arc tholeiite, B-composite field of MORB, calc-alkaline basalt and island arc tholeiites, C- calc-alkaline basalt, D-MORB. Symbols are same as figure 15.

The binary Ti/Y vs. Nb/Y discrimination plot (Pearce, 1982) used for ND, AD and PD samples are shown in figure 41. The mafic dyke compositions mostly relate to MORB but some of PD, AD and ND plotted outside the fields. Rollinson (1993) suggested that any tectonic discrimination involving Nb should be used very carefully because the content of Nb less than 10 ppm cannot be analysed by XRF technique but in the present study Nb is observed more than 10 ppm in ND and AD but in PD Nb measures less than 10 ppm (Table 13, 14 & 15). The ratio of Ti/Y shows slightly negative correlation with Nb/Y in PD whereas ratio of Ti/Y shows positive correlation with Nb/Y in ND. Nb*2-Zr/4-Y contents of ND, AD and PD samples cluster in A-II field and suggest their affinity with both within plate alkali basalt and within plate tholeiite (Meschede, 1986). One sample each from ND and PD plot in E-type MORB, N-type MORB and volcanic arc basalt respectively (Fig. 42).
Based on Ti vs. V binary plot of ND, AD and PD most of the samples have shown relation with ocean floor basalt having Ti/V ratio within 20 and 50 (Shervais, 1982). Some of the samples from PD and ND lie between Ti/V ratio of 10 and 20 as well as 50 and 100 respectively. Maximum samples of ND, AD and PD, however, have shown affinity with MORB and continental flood basalt (Fig. 43). In terms of Ti vs. Cr content (Pearce, 1975) most of the ND, AD and PD samples plot in the ocean floor basalt (OFB) but a few from PD and AD have shown transitional type between OFB and low-K tholeiite (LKT) as shown in figure 44. Pearce and Norry (1979) suggested a binary discrimination diagram based on Zr/Y vs. Zr for recognition of tectonic settings of the basaltic series. Most of the samples from ND, AD and PD have shown affinity with MORB but some PD samples plot outside the tectonic fields. A few samples of ND have more compositional affinity with within plate basalts (Fig. 45). However, a strong positive correlation between of Zr/Y and Zr in the samples of ND, AD and PD has been observed, which could be a result of source composition or melt contamination due to assimilation of the crust.
Fig. 43 Ti vs. V discrimination plot for ND, AD and PD after Shervais, 1982. The fields of continental flood basalt and MORB are also Shervais (1982) as given in Rollinsion (1993). Symbols are same as figure 15.

Fig. 44 Ti-Cr plot for ND, AD and PD showing separation trend of LKT and OFB (Pearce, 1975). Symbols are same as figure 15.

Fig. 45 Zr/Y vs. Zr discrimination diagram of ND, AD and PD after Pearce and Norry (1979). Symbols are same as figure 15.
The incompatible trace element ratios (Zr/Nb, La/Nb, Ba/Nb, Ba/Th, Rb/Nb, Th/Nb, Th/La and Ba/La) characteristics of the primitive mantle, N-MORB (normal mid oceanic ridge basalt), P-MORB (primitive mid oceanic ridge basalt), continental crust, HIMU OIB (high Mu mantle), EMI OIB (enriched mantle-I), EMII OIB (enriched mantle-II) can be considered for basalt characterization in source and tectonics (Saunders et. al. 1988 and Weaver, 1991). These values were compared with the average values of ND, AD and PD samples (Table. 25). The average Zr/Nb ratios of ND, AD and PD are related with primitive mantle value whereas average ratios of La/Nb, Ba/Nb, Rb/Nb, Th/Nb and Ba/La of ND, AD and PD can correlate with continental crust reservoirs. But the average ratios of Th/La of ND, AD and PD have compositional similarity with N-MORB. The average ratio of Ba/Nb, which is very sensitive to crustal contamination, of ND, AD and PD are 102.37, 18.46 and 28.29 respectively. These indicate that the mafic dykes of ND, AD and PD might have undergone some crustal contamination of variable degrees either prior to intrusion or during the ascent and emplacement of the mafic dyke magmas at higher crustal levels.

Some of the most important incompatible elements like K\textsubscript{2}O, Ba, Sr, Zr, Rb and Nb can also be used to characterize the basalts originated in different tectonic settings (BVSP, 1981). The range of the above mentioned incompatible trace elements for ND, AD and PD has been compared with those of oceanic island tholeiite (OIT), oceanic island alkali basalt (OIAB) and mid-oceanic ridge basalt (MORB) (Table. 26). The range of K\textsubscript{2}O (wt.%), Rb and Sr for ND and AD is comparable with OIAB whereas K\textsubscript{2}O (wt.%) and Sr of PD are related with OIT. The range of Nb for ND, AD and PD correlates well with the value of OIT. Ba and Zr contents of ND, AD and PD do not lie in any specific basalt type.

5.3.4 Geothermometers based on melt composition

The studied mafic dykes (ND, AD and PD) have undergone fractional crystallization of different degrees and contain the mineral assemblages of olivine (ol), clinopyroxene (cpx) and plagioclase (pl) with some other accessory minerals like, biotite, amphibole, magnetite,apatite, sphene and minor quartz. French and Cameron (1981) suggested that the order of crystallizing mineral phases (ol-cpx-pl) in basalt melt, their crystallizing temperatures at constant pressure (1 atmosphere) and type of basalt can be deduced from the major-oxides (SiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3} and MgO) compositions using the experimentally calibrated results (Fig. 46 & 47). In this calibration classes of basalt can be identified depending upon the different temperature of crystallization of the mineral phases. According to French and Cameron
(1981), tholeiitic and olivine tholeiites including Hawaiian and continental basalts can crystallize olivine, clinopyroxene and plagioclase in order of paragenetic sequence (shown by CLASS-1). If the crystallization is in the order of olivine, plagioclase and clinopyroxene, it is then typical of alkaline olivine basalt such as found in oceanic island basalt (shown by CLASS-2). If the plagioclase crystallizes first and followed by the crystallization of olivine and clinopyroxene, then such phenomenon is dominantly found in the calc-alkaline island arc and continental margin (shown by CLASS-3). The last and very rare occurrences of crystallization of the basalt which has crystallization sequence of plagioclase, olivine followed by clinopyroxene (CLASS 4). This order of crystallization is not commonly observed but sometime found associated with island arc volcanic.

The whole-rock compositions of the ND, AD and PD were projected on the binary diagram of $\text{Al}_2\text{O}_3$ vs $\text{MgO}$ (Fig 46a). It suggests that the crystallization of most of the ND melt in the temperature range of 1150°C to 1200°C typically belonging to CLASS 3 basalt type (calc-alkaline island arc and continental margin) but a few ND crystallized within the temperature range of 1140°C to 1175°C and show affinity with CLASS 1 basalt (tholeiite, olivine tholeiite and continental basalts). Five samples of AD show their crystallizing temperature range of 1175°C to 1220°C relating with the CLASS 2 of alkali olivine basalt found in oceanic island. Two AD samples show affinity with CLASS 1 basalt showing crystallization temperature range of 1170°C to 1200°C. The crystallizing temperature range of PD samples lies between 1140°C and 1220°C isotherms and fall into the CLASS 3 basalt type. The errors of estimated crystallizing temperatures of the mineral phases might vary from a minimum 6°C to maximum of 27°C.

When the samples of ND, AD and PD were projected onto cationic Si-Mg-Al ternary diagram (French and Cameron, 1981), the crystallizing temperatures of ND range from 1160°C to 1225°C showing affinity with CLASS 3 basalt except two ND samples, which lie transitional between CLASS 1 and 2 but the AD samples show temperature range of 1200°C to 1275°C indicating their compositional affinities with CLASSES 1, 2 and 3. The PD samples show crystallizing temperature range of 1175°C to 1250°C and cluster within the CLASS 3 basalts (Fig. 46b). After examining both the $\text{Al}_2\text{O}_3$ vs $\text{MgO}$ binary and cationic Si-Mg-Al ternary diagrams, it can be inferred that most of ND samples are consistent with CLASS 3 basalt type whereas most AD samples show consistency with CLASS 2 basalt. The PD samples have similarity with CLASS 3 basalt type. The order of crystallization of the mineral phases (pl-cpx-ol) of CLASS 3 appears valid for ND and PD whereas in AD the crystallizing order is more likely in the sequence of ol-pl-cpx. These observations are
consistent with petrographic and mineral chemical investigations. However, olivine is observed in only AD but ND and PD are devoid of olivine phase.

![Diagram](image)

Fig. 46 (a) Compositions of ND, AD and PD in terms of MgO (wt.%) vs. Al2O3 (wt.%). The classes and fields are taken from Cameron and French (1981). Note see the text for explanation. Symbols are same as figure 15.

![Diagram](image)

Fig. 46 (b) Compositions of ND, AD and PD in terms of Si-Mg-Al. The classes and fields are taken from Cameron and French (1981). Note see the text for explanation. Symbols are same as figure 15.

5.4 GEOCHEMICAL CHARACTERISTICS

The geochemical features of mafic dykes have been used to characterize the nature of the constituent elements and their correlation to each other. Moreover, the concentration and nature of distribution of major and trace including the rare earth element (REE) of mafic dykes of ND, AD and PD have been described to decipher the processes in the evolution of mafic dyke magmas. In this section, an attempt has also been made to understand the effect of contamination to the primary compositions and chemical changes of the ND, AD and PD. The geochemical features of the ND, AD and PD have also been compared with the
published geochemical data of Bhimtal volcanics (BV) and Berinag volcanics (BNV) of Kumaun Lesser Himalaya, in order to establish geochemical relations between them, if any.

5.4.1 Major oxide characteristics

Forty-six representative samples from ND (N=18), AD (N=7) and PD (N=21) were analysed for the major oxides and trace including the rare earth element (REE) and the obtained results are discussed below.

5.4.1.1 Nainital dykes (ND)

The major oxides (wt. %) and CIPW norms of ND are shown in the table 10. The average and standard deviation of each major oxide of ND are also given in the table 19. The SiO₂ content of ND ranges from 43.48 to 51.03 wt.%, Al₂O₃ from 13.29 to 16.35 wt.%, MgO from 5.62 to 8.61 wt.%, Fe₂O₃ from 10.34 to 12.92 wt.%, K₂O from 0.71 to 2.71 wt.%, TiO₂ from 1.08 to 5.67 wt.% and Mg# (100 Mg/Mg+Fe²⁺) from 52.33 to 66.85. The ND samples mostly exhibit quartz or olivine normative compositions but are devoid of corundum norm. It suggests that the ND samples are not altered and not much contaminated. Plagioclase (Or, Ab, An), pyroxenes (Di, Hy), olivine, Fe-Ti oxides (ilmenite, magnetite) and apatite normative minerals are common in all the ND samples. However, hypersthenes (Hy) norm is not present in three ND samples (Table 10).

Alfred Harker (1909) used binary plots as SiO₂ vs. other various oxides to understand the involved magmatic processes for the suite of magmatic rocks, which are popularly known as Harker’s variation diagram where SiO₂ is considered as an index of differentiation. Later on, MgO and FeO/MgO, cation based Larsen Index, and normative based differentiation or solidification indices were also used to infer the magmatic processes of igneous rocks. In conjunction to SiO₂ and MgO, Mg# (Mg number) was also preferred for understanding the magmatic processes because it is not affected by the process of crystal accumulation. Mg# therefore provides better information to the petrogenetic process of crystal fractionation and partial melting (Cox et. al., 1979).

The degree of SiO₂ variation in ND is more than that of MgO. Major oxides (TiO₂, Al₂O₃, Fe₂O₃, MgO, MnO, CaO, Na₂O, K₂O, and P₂O₅) of ND samples were plotted against SiO₂ (Fig. 47a-i). TiO₂, MgO and CaO contents have shown negative correlation with the increasing SiO₂ content (Fig. 47a, d, f). There is a compositional gap in TiO₂ content (3 to 4.2 wt.%) of ND samples thereby showing bimodal distribution but have shown same trend of decreasing pattern with increasing SiO₂ content. Na₂O, Fe₂O₃, MnO and P₂O₅ have shown
slightly positive correlation with increasing SiO$_2$ content (Fig. 47g, c, e, i). K$_2$O and Al$_2$O$_3$ contents show scattered pattern (Fig. 47h, b). The major oxides (TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MnO, CaO, Na$_2$O, K$_2$O, and P$_2$O$_5$) contents of ND have also been tested against MgO because MgO is considered as more appropriate index of differentiation for mafic rocks. Al$_2$O$_3$, K$_2$O and to some extent Fe$_2$O$_3$ contents decrease with increasing MgO content. TiO$_2$ content of one group of ND samples also show negative correlation with the MgO content whereas another group of five ND samples correlated positively with MgO (Fig. 48a). CaO content shows strong positive correlation with MgO (Fig. 48e) but the MnO and Na$_2$O appear constant with increasing MgO content. P$_2$O$_5$ and Al$_2$O$_3$ show data scatter (Fig. 48d, f).

5.4.1.2 Almora dykes (AD)

The major oxides (wt.%) and CIPW normative values of AD are shown in the table 11. The average and standard deviation of each major oxide of AD are also given in the table 19. The SiO$_2$ content of AD ranges from 43.43 to 46.11 wt.%, Al$_2$O$_3$ from 12.31 to 15.89 wt.%, MgO from 8.11 to 9.75 wt.%, Fe$_2$O$_3$ from 11.89 to 13.97 wt.%, K$_2$O from 1.37 to 1.83 wt.%, TiO$_2$ from 1.15 to 1.70 wt.% and Mg# from 57.14 to 63.88. Table 11 shows the normative component of the AD samples. AD exhibit diopside, feldspar (Ab-An-Or), olivine, magnetite, ilmenite and apatite normative compositions, which best occupy the olivine tholeiite type of magma in basaltic tetrahedron (Yoder and Tilley, 1962). The samples of AD are devoid of corundum norm and exhibit low variation of TiO$_2$ content, which together indicate least crustal contamination.

The major oxides (TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MgO, MnO, CaO, Na$_2$O, K$_2$O, and P$_2$O$_5$) have been plotted against SiO$_2$ for AD samples (Fig. 47). Due to less number of samples, the oxides do not show distinct correlation with the SiO$_2$ content instead they show scattered patterns, except Fe$_2$O$_3$ and K$_2$O which show negative and positive correlations with SiO$_2$ respectively (Fig. 47c, g). The major oxide (TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MnO, CaO, Na$_2$O, K$_2$O, and P$_2$O$_5$) contents of AD have also been plotted against MgO content. Only CaO and K$_2$O show decreasing trends with increasing MgO content indicating their incompatible character (Fig. 48e, g). On the bivariate diagrams, the data scatter has been observed for Al$_2$O$_3$, Fe$_2$O$_3$ and P$_2$O$_5$ (Fig. 48 b, c). TiO$_2$, MnO and Na$_2$O contents of AD samples remain constant with increasing MgO content (Fig. 48a, d, f), which are probably conserved in the AD magma during its evolution.
5.4.1.3 Pithoragarh dykes (PD)

The major oxides (wt.%) and CIPW normative values of PD are shown in the table 12. The average and standard deviation of each major oxide of PD are also given in the table 19. The SiO₂ content of PD ranges from 42.67 to 47.02 wt.%, Al₂O₃ from 14.78 to 16.81 wt.%, MgO from 5.11 to 8.91 wt.%, Fe₂O₃ from 10.80 to 14.97 wt.%, K₂O from 0.37 to 0.98 wt.%, TiO₂ from 0.58 to 2.77 wt.% and Mg# from 48.39 to 68.75. Table 12 shows the normative component of the PD samples. PD samples mostly exhibit pyroxene (Di-Hy), feldspar (Ab-An-Or), olivine, magnetite, ilmenite and apatite normative compositions, which suggest olivine tholeiite type of magma in basaltic tetrahedron (Yoder and Tilley, 1962). PD samples are devoid of corundum normative component. The variation of TiO₂ content of PD samples is higher as compared to AD samples indicating that PD samples have undergone some degrees of crustal contamination, particularly for PD groups having high-TiO₂ content.

The major oxide (TiO₂, Al₂O₃, Fe₂O₃, MgO, MnO, CaO, Na₂O, K₂O, and P₂O₅) contents have been plotted against SiO₂ content for PD samples (Fig. 47). Fe₂O₃ has shown perfect negative correlation with SiO₂ content (Fig. 47c). Moreover, TiO₂ and P₂O₅ contents of PD samples have also shown slight negative correlation with the increasing SiO₂ content (Fig. a, i). MgO content increases slightly with increasing SiO₂ content (Fig. 47d). Na₂O, Al₂O₃, and CaO exhibit scattered distribution against SiO₂ content whereas MnO and K₂O seem to be constant with increasing SiO₂ content (Fig. 47e, h), and therefore these oxides may represent conserved elements in PD magma. The major oxides (TiO₂, Al₂O₃, Fe₂O₃, MnO, CaO, Na₂O, K₂O, and P₂O₅) contents of PD have also been plotted against MgO. Overall CaO, Al₂O₃, K₂O and Fe₂O₃ contents decrease with increasing MgO content but show poor negative correlation with MgO (Fig. 48e, b, g, c). TiO₂ and P₂O₅ contents indicate data scattering whereas MnO and Na₂O exhibit almost constant distribution with increasing MgO content (Fig. 48d, f).

After examining the distribution patterns of various major oxides and nature of correlation with SiO₂ and MgO for ND, AD and PD, it can be inferred that the MnO content in ND, AD and PD remains more or less constant with increasing SiO₂ and MgO contents. The observed major oxide variations in ND, AD and PD suggest that plagioclase, clinopyroxene and olivine assemblage might have participated during fractional differentiation of respective mafic dyke magmas. However, the observed scattering patterns of Al₂O₃, K₂O, P₂O₅, Fe₂O₃ and TiO₂ suggest the post magmatic alkali diffusion as well as crustal contamination during the ascent of mafic dyke magmas. Whole rock Mg# (Mg/Mg+Fe³) ranges from 0.48 to 0.69 in PD and 0.57 to 0.64 in AD suggests evolved nature
of mafic dyke magma whereas variation in Mg# in ND from 0.29 to 0.69 may be due to moderately evolved nature.

Fig. 47 (a-i) Harker variation diagram of major oxides (wt.%) compositions of ND, AD and PD plotted against SiO$_2$. Symbols are same as figure 15.
Fig. 48 (a-h) shows bivariate diagrams of all major oxides against MgO (wt.%) for ND, AD and PD. Symbols are same as figure 15.
5.4.2 Trace element characteristics

The trace elements are those elements whose concentration level is below 0.1 wt.% in the igneous rocks. Their activities \((a_i)\) in the melts are variable and have direct relation to their concentration \((x_i)\) in the system and obey the Henry’s Law (Hanson, 1980, 1989). During the processes of partial melting and fractional crystallization, the trace elements show their affinity either with melt or mineral phases. Trace elements which preferentially partitioned in the melt phases are referred as *incompatible* \((K_D \text{ or } D<<1)\) and those elements which have preference to mineral phases are referred as *compatible* \((K_D \text{ or } D\geq 1)\) elements. Based on chemical properties the elements can be divided into two subgroups viz high-field strength elements (HFSE) which include REE, Th, U, Ce, Pb\(^{4+}\), Zr, Hf, Ti, Nb, Ta whereas low-field strength elements (LFSE) are comprised of K, Rb, Cs, Ba, Pb\(^{2+}\), Sr, Eu\(^{2+}\). These LFSE are also known as large ion lithophile elements (LILE) and are more mobile if fluid or vapour phases are involved. Trace element geochemistry is therefore effectively used to infer the processes involved during the evolution of the magmatic rocks and to characterize the nature of the source or reservoir of the rocks in question. All the forty-six analysed samples of ND, AD and PD have been used for trace element interpretation because they represent the primary compositions as defined by the CIA value less than 50% as well as preservation of primary phases observed in petrographic study. Here an attempt has also been made to compare mantle- and chondrite-normalized trace and rare earth element patterns respectively with the Precambrian Himalayan mafic volcanics.

5.4.2.1 Nainital dykes (ND)

The trace element \((Cr, Ni, Co, Sc, V, Pb, Zn, Rb, Cs, Ba, Sr, Ga, Ta, Nb, Hf, Zr, Y, Th, U)\) contents of ND samples are given in table 13. All trace elements have been plotted against MgO content for ND (Fig. 49a-o). Cr, Co, V, Y, Rb, Sr, Nb, Hf contents have shown two cluster with respect to MgO content. Cr and Zr contents in ND exhibit positive correlation with the increasing MgO content (Fig. 49a, k) whereas Th content shows negative correlation with MgO content (Fig. 49i). The other trace elements like Sc, Cu, Pb and Zn contents are more or less remain constant either with increasing or decreasing MgO content (Fig. 49d, f, g, h). The bivariate diagrams plotted for various trace elements against MgO content did not give much information about the magmatic processes of the ND samples. Among the LILE group, anomalously high content of Sr (548-2913 ppm) and Ba (548-6368 ppm) in ND can be observed (table 13). The Rb (18-50 ppm) content is also substantially low as compared to AD and PD samples. The HFSE such as Zr (71-517 ppm) and U (0.19-0.86
ppm) in ND samples show large and restricted variations respectively. Other HFSE such as Th, Ta, Nb, Sm, HF and Y show moderate degree of variations in their content (table 13). Rb and Ba show wide variations in their content and behave as incompatible in ND whereas transitional elements viz. Ni, Cr, Co and V contents vary moderately and behave as compatible elements in ND, which together indicate that the ND magma is crustally-contaminated and subsequently may have undergone low degree of fractional differentiation. High Ba/Nb (28-459 ppm), Ba/Zr (1.06-65 ppm) and Ba/Y (15-204 ppm) ratios of ND samples are comparable to the basaltic rocks that have been contaminated with crustal components, within the mantle or during the ascent of mafic dykes magma through the crust (e.g. Sano and Fuju, 1996; Melluso et. al 1999; Khadri et. al 1999).

Mantle-normalized (Sun and McDonough, 1989) multielement (arranged in order of increasing compatibility with respect to a small percentage melt of mantle) variation diagrams commonly known as spidergram, have been plotted and compared with Precambrian mafic volcanics of Himalayan region. Mantle-normalized (Sun and McDonough, 1989) trace element variations of ND are shown and compared with those of Precambrian mafic volcanics of Himalayan region (Fig. 50c). ND samples show relatively depleted (negative) patterns for Rb, Th, K, Ce, P and Y whereas Ba, U, Sr, Zr, Sm, have shown positive anomalies in their mantle-normalized patterns. Ba and Sr exhibit strong positive anomalies and P shows strong negative anomaly in ND. Normalized values of K, Rb, Th, U, Ta, Ti and Y of ND lie within the variation field of Precambrian Himalayan mafic volcanics but Nb, La, Ce, Nd and Sm of ND follow the upper or sometime beyond the limit of Precambrian Himalayan volcanics (Figs. 50c). The remarkable feature is that the Sr exhibits strong positive anomaly in ND whereas strong negative anomaly has been observed for the most Precambrian mafic volcanics of Himalayan region (Figs. 50c). The observed low degree of positive Ti anomaly in some ND samples may be accounted to early crystallization of iron-titanium (Fe-Ti) oxides but depletion in P appears related to the source region of the ND magma.

5.4.2.2 Almora dykes (AD)

The trace element (Cr, Ni, Co, Sc, V, Pb, Zn, Rb, Cs, Ba, Sr, Ga, Ta, Nb, Hf, Zr, Y, Th, U) contents of AD samples are given in the table.14. All trace elements have been plotted against MgO content (Fig. 49). Unfortunately, none of them have given any definite trend of positive or negative correlation with MgO. This may be due to the inadequate number of AD samples. Hf, Pb and Co show very scattered patterns whereas Cr, Sc, V, Cu, Zn, Th, Y, Rb, Sr, Nb, Zr contents have shown clustering of data against MgO on most bivariate plot, being
restricted in the variation range (Fig. 49a-o). Therefore trace element variation diagrams against MgO do not provide much petrogenetic information above the AD samples. Among the LILE, anomalously high Sr (782-1612 ppm) and Ba (1118-5829 ppm) in AD samples have been observed (table 14). The Rb (20-83 ppm) content is also low in AD samples. The HFSE such as Zr (24-485 ppm) shows large variation but least in U (0.23-0.91 ppm). Other HFSE such as Th, Ta, Nb, Sm, Hf and Y show moderate degree of variations in their content (table 14). Rb, Sr and Ba also show wide variations in their content and behave as incompatible which suggest that the AD dyke magma has undergone low degree of fractional crystallization. The range of Ba/Nb (75-411 ppm), Ba/Zr (4-75 ppm) and Ba/Y (39-183 ppm) of AD samples are high, which suggest varying degrees of crustal contamination.

Mantle-normalized spidergrams of AD samples show depletion in Rb, Th, K, Ce, P, Ti whereas Ba, U, La, Sr, Zr, Sm show enriched positive anomalies in their mantle-normalized patterns but Zr shows wide variation in the normalized pattern. Ba and Sr exhibit strong positive anomalies and P shows strong negative anomaly. Rb, Th, U, K, Ta, Ti and Y lie within variation field but Nb, La, Ce, Nd and Sm follow the upper limit or even beyond when compared with those of Precambrian Himalayan mafic volcanics (Figs. 50b). All AD samples show Sr positive anomaly which should be due to the plagioclase accumulation whereas strong depletion in P may be accounted by a number of processes such as retention of phosphorous-bearing phases in source or fractionation from magma, contamination by continental crust, or hydrous metasomatism of depleted mantle (e.g. McCuaig et. al., 1994).

5.4.2.3 Pithoragarh dykes (PD)

The trace element (Cr, Ni, Co, Sc, V, Pb, Zn, Rb, Cs, Ba, Sr, Ga, Ta, Nb, Hf, Zr, Y, Th and U) contents of PD samples are given in the table 15. All trace elements have been plotted against MgO content on bivariate plots (Fig. 49a-o). Cr, Sc, Cu, V contents of PD samples are much higher than that of ND and AD samples (Table 15, Fig. 49a, d, f, e). The contents of Th, Zr, Hf and Sr in PD are lesser than that of ND and AD samples. Pb, Zn and Co contents form large data scatter whereas Sr and Hf contents broadly remain unchanged with the increasing MgO content (Fig. 49o, n), having minimal variations in their contents. Cr, Sc, V and Cu contents are higher and Th, Zr, Hf and Sr are lower as compared to those of ND and AD samples (Fig. 49i, k, n, o). Among the LILE element, Sr (121-258 ppm) and Ba (58-596 ppm) are present in low amount in PD samples (table 15). The Rb (11-65 ppm) content is substantially lower as compared to AD and ND samples. The HFSE such as Zr has 36-430 ppm whereas U shows 0.06-0.58 ppm depicting large variation in Zr but least
variation in U content. Other HFSE such as Th, Ta, Sm, Hf, Y and Nb show moderate degree of variations in their contents except one PD sample which exhibits high Y and Nb contents suggesting their common behaviour (Table 15). Rb and Ba also show wide variations in their contents and behave as incompatible elements in PD whereas Ni, Cr, Co and V contents vary moderately and behave as compatible in PD. Although the variations of Sr and Ba in PD samples are narrow in comparison to ND and AD samples, the PD magma appear to have undergone very low degree of fractional crystallization.

Fig. 49 (a-h) shows bivariate plots of trace and rare earth element of ND, AD and PD. Symbols are same as figure 15.
Fig. 49 (i-o) shows bivariate plots of trace and rare earth element for ND, AD and PD. Symbols are same as in figure 15.

Mantle-normalized (Sun and McDonough, 1989) trace elements patterns of PD have shown depletion in Ba, Th, U, Ta and enrichment in P as compared to Precambrian mafic
volcanics of Himalayan region (Fig. 50a). PD samples have shown positive anomalies for Ba, U, Ta, La, Nd, Sm, Ti and negative for Rb, th, K, Sr, P on their mantle-normalized patterns. Ba shows strong positive anomaly whereas P exhibits negative anomaly. Rb, K, Nb, La, Ce, Sr, Ti and Y of PD lie within the variation field but Ba, Th, U, Ta, P and Zr extend even beyond the limit of Precambrian Himalayan mafic volcanics (Figs. 50a). The remarkable feature is that the Sr and P exhibit slight negative anomalies as comparison to strong negative anomaly observed for the Precambrian mafic volcanics of Himalayan region (Figs. 50a). The observed negative anomalies for Ti and P in PD may be due to early fractionation of iron-titanium (Fe-Ti) oxides and apatite during crystallization or related to the source region.

Rb and K exhibit depletion in ND, AD and PD, which may account for varying degrees of crustal contamination or effect of secondary processes acted upon them. Strong positive anomaly for Sr in ND and AD could be explained by differential degrees of fractional crystallization of mafic dyke magmas. Small negative Nb anomaly indicates a low degree of contamination of melt with the lower continental crust (Wilson 1989, Rollinson, 1996).
5.4.3 Rare earth element (REE) characteristics

Rare earth elements (REE) are those elements having atomic number 57 to 71 in the Lanthanides series of the periodic table. They have a differently unique character from rest of the elements in the periodic table and constitute fifteen elements such as La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. Out of these Pm does not occurred in nature. The REE characters of magma are influenced by the different magmatic processes that can ultimately cause REE to undergo fractionation relative to each other. REE are very useful in the petrogenetic studies of the mafic rocks since they form a coherent group of incompatible elements and are relatively immobile even during the moderate degree of metamorphism and weathering (Hanson, 1980 and Bernard et. al., 1991). The REE tend to concentrate in the melt and are insensitive to crystal fractionation, except Eu, thereby good indicators of source of the basaltic rocks.

5.4.3.1 Nainital dykes (ND)

Chondrite normalized (Taylor and McLennan, 1985) REE patterns of ND samples have been compared with those of mafic volcanics of Himalayan region (Fig. 51c). The REE content (ppm), chondrite-normalized values and normalized ratios (LaN/LuN), (CeN/YbN), (LaN/YbN), (LaN/SmN), (GdN/YbN) and (EuN/Eu*) of petrogenetic significance of mafic dykes are also given in table 16. Normally LaN/LuN ratio, as an index of LREE to HREE
fractionation, of ND ranges from 7.35 to 15.35, which suggest moderate degree of LREE to HREE fractionation. Two samples (ND-M-21, ND-IM-21) exhibit high La/N/LuN ratios (14.2-15.35), which could be caused by secondary processes. ND shows strong positive Eu-anomaly (EuN/Eu*=1.48-2.45) but moderate degree of negative Eu anomalies has been observed for mafic volcanics of Himalayan region (Fig. 51c). These are likely a reflection of plagioclase-rich source region or an effect of plagioclase accumulation. Sum of the total REE varies from 89.13 to 203.90 ppm in ND. LREE show relatively flat and wide variation patterns but inclined and shrinked HREE patterns with moderate degree of positive Eu-anomalies in ND. This has been compared with Precambrian mafic volcanics of Himalaya region, which show more or less similar patterns for LREE but differ remarkably in HREE patterns and Eu-anomalies (Fig. 51c).

5.4.3.2 Almora dykes (AD)

The REE content (ppm), chondrite normalized values and normalized ratios (LaN/LuN), (CeN/YbN), (LaN/YbN), (LaN/SmN), (GdN/YbN) and (EuN/Eu*) of petrogenetic significance of mafic dykes are given in table 17. The chondrite-normalized (Taylor and McLennan, 1985) REE patterns of AD have also been compared with those of the Precambrian mafic volcanics of Himalaya region (Fig. 51b). LaN/LuN ratio of AD ranges from 9.99 to 17.64 but three samples (AD-M-24, AD-IM-24 and AD-C-24) show high LaN/LuN ratios (13.46-17.64). It could be due to secondary processes. Eu shows a moderate degree of positive anomalies (EuN/Eu*=2.13-2.40). Sum of the REE varies from 151 to 223 ppm and exhibits strong degree of LREE to HREE fractionation as compared to those of ND and PD. The chondrite normalized patterns of AD have similarity with that of ND showing slightly flat LREE and inclined HREE patterns with moderate degree of positive Eu-anomalies. It suggests that the AD have experienced plagioclase fractionation or have derived from the plagioclase rich sources.

5.4.3.3 Pithoragarh dykes (PD)

Chondrite normalized (Taylor and McLennan, 1985) REE patterns of PD samples have been compared with those of mafic volcanics of Himalayan region (Fig. 51a). The REE content (ppm), chondrite normalized values and normalized ratios (LaN/LuN), (CeN/YbN), (LaN/YbN), (LaN/SmN), (GdN/YbN) and (EuN/Eu*) of petrogenetic significance of mafic dykes are also given in table 18. Normally LaN/LuN ratio of PD ranges from 2.56 to 10.60, which suggest low to moderate degree of LREE to HREE fractionation. PD show slight or no Eu-
anomalies ($\text{Eu}_\text{N}/\text{Eu}^* = 0.83-1.15$) (Fig. 51a), which strongly suggest less or no role of plagioclase during the fractionation or melting events. Sum of the REE varies from 48 to 191 ppm in PD. LREE show almost flat and much wide variation patterns compared to inclined and shrinked HREE patterns with no or less Eu-anomalies. Precambrian mafic volcanics of Himalaya region show more or less similar LREE patterns but differ in HREE patterns and Eu-anomalies as compared to those of PD (Fig. 51a).

The chondrite-normalized REE patterns of ND, AD and PD are almost similar with the adjoining Precambrian mafic volcanic of Himalaya region except in Eu anomalies.

5.5 GEOCHEMICAL COMPARISON WITH BHIMTAL VOLCANICS (BV)

In order to get clear understanding of the geochemistry of mafic dykes of ND, AD and PD in KLH, it is pertinent to compare the geochemistry of the mafic dykes with those of the published data of BV exposed in the outer segment of KLH of northwestern Himalaya. These volcanic activities are considered to be occurred in vast extensive during the Palaeoproterozoic (ca 1.8 Ga). For comparison the published data on BV (Pandey and Kumar, 2006, 2007) have been used and plotted on some important binary and ternary discrimination diagrams (Figs. 52-66). The averages major-oxides, trace and rare earth elements contents of ND, AD, PD and BV are also given in the tables 19, 20 and 21.
5.5.1 Geochemical characteristics

BV are either quartz or olivine tholeiite basalts on the basis of the CIPW normative classification. The major normative minerals are quartz or olivine, plagioclase, pyroxene, magnetite, ilmenite and apatite but are devoid of corundum norm. In term of TAS, the ND, AD and PD belong to basalt, picro-basalt and slightly basanite whereas BV are basalt to basaltic andesite (Fig. 52a). Being basaltic in composition silica percentage is lower in ND, AD and PD in comparison to BV thereby they have picro-basalt to basanite compositions. The wide variation in alkali contents of BV is observed but maximum alkali content is
observed in mafic dykes (Fig. 52b). BV are subalkaline (tholeiite) in nature with slight alkaline affinity whereas ND, AD and PD are subalkaline to alkaline in nature (Fig. 53). In term of FeO*-Na2O+K2O-MgO diagram the BV show iron enrichment tholeiite trend as similar by exhibited by ND, AD and PD (Fig. 54). A few ND show affinity with calc-alkaline basalt. Both the BV and samples of ND, AD and PD have shown common compositional trend i.e. transitional between high-Fe and high Mg tholeiites. It is also observed that BV have relatively lower Al2O3, alkali contents and higher amount of Fe2O3 as compared to ND, AD and PD (Fig. 55). Nb/Y vs. Zr/TiO2 binary diagram shows wide compositional variations for ND, AD, PD and BV (Fig. 56). BV have however lower Nb/Y ratio whereas ND, AD and PD have wider variation of Zr/TiO2 ratio with almost constant Nb/Y ratio, probably indicating strong fractionation of Fe-Ti oxides in the mafic dykes. Most of the BV show basalt to andesite compositions of subalkaline basalt whereas ND, AD and PD are subalkaline to mostly alkaline in nature. R1 vs. R2 binary plot of De La Roche et. al., (1980) suggests silica saturated basaltic (gabbro to gabbro norite) affinity of ND, AD and PD whereas BV have shown gabbro, dorite and monzodiorite compositions (Fig. 57).

Fig. 52 (a) Total alkali vs. Silica diagram (TAS) of Le Maitre, 2002. Shaded area shows the compositional field of BV. Symbols are same as figure 15.
Fig. 52(b) K$_2$O vs. SiO$_2$ classification of Le Maitre (2002). Shaded area shows the compositional field of BV. Symbols are same as figure 15.

Fig. 53 Total vs. Silica diagram, after Irvine and Baragar (1971). Shaded area shows the compositional field of BV. Symbols are same as figure 15.

Fig. 54 AFM diagram after Irvine and Baragar, 1971. Note shaded area shows the compositional field of BV. Symbols are same as figure 15.

Fig. 55 Al$_2$O$_3$-(FeO+TiO$_2$)-MgO ternary diagram (Jenser, 1976) of ND, AD and PD compared with BV. Symbols are same as figure 15.

Fig. 56 Zr/TiO$_2$ vs. Nb/Y ratio plot of ND, AD and PD after Winchester and Floyd (1977) compared with BV compositional field shown (shaded). Symbols are same as figure 15.
5.5.2 Tectonomagmatic relationships with BV

Some tectonomagmatic discriminations diagrams have been plotted to understand the relationships of tectonomagmatic environments between BV and mafic dykes (ND, AD and PD). In terms of K$_2$O-TiO$_2$-P$_2$O$_5$ components the BV and ND, AD, PD have shown coherent compositions similar to continental basalts but higher content of P$_2$O$_5$ can be observed in mafic dykes (ND, AD, PD) as compared to BV (Fig. 58).

**Fig. 58** TiO$_2$-K$_2$O-P$_2$O$_5$ discrimination ternary diagram, after Pearce et. al. (1975). Shaded area shows the BV compositional field. Symbols are same as figure 15.

BV cluster in mostly in the field of continental basalts and some in MORB but ND, AD and PD have shown more affinities with island arc basalts and active continental margin basalts in FeO$^\text{t}$-MgO-Al$_2$O$_3$ ternary plot (Fig. 59). In terms of HFSE (Ti, Zr, Y and Nb) the ND, AD, PD and BV overlap in the MORB and calc-alkaline basalts. Most of the ND, AD and PD plot in within plate alkali-basalt and within plate tholeiites whereas BV largely show affinity with
N-type MORB and volcanic arc basalts (Fig. 60a & b). BV show compositional affinity with MORB but a few are close to within plate basalts whereas ND, AD and PD have very wide variation of Zr/Y ratio as compared to BV. Most of the ND, AD and PD within the MORB field but a few of ND show within plate basalt affinity. Some samples of ND and PD also fall outside the fields. Zr/Y ratio of ND, AD and PD shows strong positive correlation with increasing Zr content (Fig. 61). In terms of Ti vs. Zr plot the content of Ti increases with increasing Zr content as a whole for ND, AD and PD samples showing wide data scatter (Fig. 62). Similarly BV samples show the same trend but the variation of Ti content is more in mafic dykes. Ti and Cr contents of BV are negatively correlated with ND, AD and PD. BV show low-K tholeiite to OFB affinities whereas mafic dykes exhibit OFB nature (Fig. 63). The Cr contents in mafic dykes are much higher than BV suggesting their evolution from the enriched mantle source. Based on Ti and V contents, the BV have shown more affinity with MORB and some are transitional between MORB and continental flood basalts. Similarly the mafic dykes (ND, AD, PD) also show more affinities with MORB and continental flood basalts (Fig. 64).

Fig. 59 FeOt-MgO-Al2O3 diagram plotted for ND, AD and PD after Pearce, 1977. Fields are same as figure 38, shaded area shows BV compositional field and symbols are same as figure 15.

Fig. 60 (a) Nb-Zr-Y ternary diagram for ND, AD and PD after Mescede (1986). Fields are same as figure 42, shaded area shows BV compositional field and symbols are same as figure 15.
Fig. 60 (b) Ti-Zr-Y triangular plot for ND, AD and PD after Pearce and Cann (1973). Fields are same as figure 39, shaded area shows BV compositional field and symbols are same as figure 15.

Fig. 61 Zr/Y vs. Zr discrimination diagram of ND, AD and PD after Pearce and Norry (1979). Fields are same as figure 45, shaded area shows BV compositional field and symbols are same as figure 15.

Fig. 62 Ti vs Zr binary plot for ND, AD and PD after Pearce and Cann (1973). Fields are same as figure 40, shaded area shows BV compositional field and symbols are same as figure 15.

Fig. 63 Ti-Cr plot for ND, AD and PD showing separation trend of LKT and OFB (Pearce, 1975). Fields are same as figure 44, shaded area shows BV compositional field and symbols are same as figure 15.

Fig. 64 Ti vs V binary diagram for ND, AD and PD after Shervais, 1982. Fields are same as figure 43, shaded area shows BV compositional field and symbols are same as figure 15.