6.1 INTRODUCTION

Palaeomagnetism is the study of the remanent magnetism in the rocks, which can be used effectively to interpret the tectonics, field variations and palaeoclimate. The palaeomagnetic study is one of the most important geological topics to infer the various magmatic episodes and proper characterization of the different magmatic bodies in the earth’s surface. The rocks are good records of the magnetic fields of the past, probably of the time of their formation. Primary objective of paleomagnetic analysis is the recognition of the Natural Remnant Magnetization (NRM) as described by Butler (1992). Contribution of magnetization in rock is of many kinds as magnetization is acquired during the formation of rock, which is known as Natural Remnant Magnetization (NRM) or primary magnetization, and when the magnetization is acquired after formation of rock is known as a secondary magnetization. Thus primary magnetization is overprinted by a younger, but weaker, secondary magnetization picked up by the earth’s current magnetic field. Recognition and erasure of the secondary component of NRM is the major goal of the laboratory analysis. The magnetism leaves some imprints of the past in the rock, in certain favourable conditions when measured in terms of magnetic directions, which give crucial information about the past. The study of magnetism is believed to be originated from the observation of the behaviour of natural permanent magnets, and one of the earliest known tools is compass needle. In general a permanent magnet is characterized by the presence of its ‘north’ and ‘south’ magnetic poles imagined to reside at the opposite ends of it (Butler, 1992; McElhinny and McFadden, 2000) which were considerably used in analyzing the behaviour of magnets till the early eighteenth century. This study is most suited in the mafic or ultramafic igneous rocks of fresh and unaltered, also in sedimentary environment but is not applicable in metamorphic rocks.

The palaeomagnetic and rock magnetic studies on mafic dykes of Nainital (ND), Almora (AD) and Pithoragarh (PD) of KLH have not been carried out so far. In this chapter, the emphasis has been given to recognize the different magmatic episodes and evolution of mafic dykes (ND, AD and PD) separately based on NRM recorded by mafic dykes. An attempt has also been made to find out the possible age of the mafic dykes of ND, AD and PD in KLH with the help of palaeomagnetism.
6.2 SAMPLE COLLECTION

The mafic dykes in KLH can be divided into three distinct groups depending on the tectonic segments in which these dykes are intruded. Nainital dykes (ND) occur in the Nainital separated by South Almora Thrust (SAT) from Almora dykes (AD), AD which encountered in the Khunt hill of Almora separated by SAT and North Almora Thrust (NAT) from ND and PD respectively. Pithoragarh dykes (PD) occur in Pithoragarh separated by NAT from AD and northern side bounded by Main Central Thrust (MCT). Petrographically, the ND are dominated by plagioclase, AD dominated with olivine and plagioclase whereas PD dominated with clinopyroxene, and these dykes belong to leucogabbro and gabbro as per IUGS classification. The AD are dark grey to greyish black in colour, melanocratic and compact with hard metallic sound. The PD and ND are greenish grey to dark grey lighter in comparison of AD. The PD and ND can be easily distinguished from AD in hand specimens due to different colours and compactness of the rocks. The ND, AD and PD have shown distinct petrophysical, petrological and geochemical features, therefore it is likely that they may have evolved by different processes.

The fresh and unaltered samples are very much important to study the palaeomagnetic investigations since altered sample does not give the primary remnant magnetization due to secondary magnetic influence in the system. Here, it is important to get aware with some terminology commonly used while collection of samples. Sites mean the exposure of the particular magmatic body. The oriented block samples from the same site denote separately depending upon the number of samples collected. The orientation of block samples is marked with the help of brunton compass (horizontal level, north marks and specimen identity) before breaking the mafic dyke samples. Normally, five oriented samples were collected from the same site for proper statistical treatment. The oriented samples are again reoriented in the instrument and were cored in the palaeomagnetic laboratory at Indian Institute of Geomagnetism (IIG), Allahabad. The cores were cut to standard cylindrical specimens (2.5cm diameter×2.2cm length with top-bottom and north marking) for measurement of NRM. Generally multiple specimens were prepared from an individual sample for additional checks on homogeneity of the NRM and experimental procedures. In the present investigation, three to four cores were prepared from each block sample and named as a, b, c & d. Each individual core was again cut into standard cylindrical size specimens and marked as a₁, a₂, a₃ or b₁, b₂, b₃ and so on.
In the present study, 54 oriented block samples (nearly 160 standard cylindrical specimens of 2.5cm diameter × 2.2cm length) were collected from 09 mafic dykes representing ND, AD and PD of KLH (Fig. 65a-d).

6.2.1 Sample processing in the laboratory

6.2.1.1 Heavy Duty Drilling Machine

The collected oriented block samples were again re-oriented in the laboratory with the help of clap or cement, and then drilled with the help of heavy-duty drilling machine having diamond bit of diameter 22.5mm and the maximum length of core 12 cm. Most of the time the length of the core obtained varies depending upon the nature of the rock type and hardly
to get 12 cm length core after coring. The block sample is fixed with the bi-horizontal moving stage which is attached with the drill machine. Manually handled liver was used, which controls the diamond core bit during the penetration. A number of precautions should be taken while drilling and coring the samples in the same manner as first block sample was fixed in the field, and the shaking of block sample during the coring must be avoided (Fig. 66a).

6.2.1.2 Diamond Blade Cutting Machine

The cores prepared from the drilling machine were cut according to their standard size of 2.2cm length with help of diamond blade cutting machine for further analytical purposes (Fig. 66b).

Fig. 66 (a) Photograph showing coring machine for making core of 2.5cm diameter standard size.  
(b) Photograph showing core cutting machine for making specimen of 2.5cm diameter with 2.2cm length.  
(c) Photograph showing Magnetic Susceptibility Meter (Model MS2)  
(d) Photograph showing JR-5A Spinner Magnetometer  
(e) Photograph showing Molspin AF Demagnetizer (UK)  
(f) Photograph showing Thermal Demagnetizer (MMTD-80), USA
6.2.1.3 Bartington Magnetic Susceptibility Meter (Model MS2)

The MS2 Magnetic Susceptibility System comprises a portable measuring instrument, the MS2 meter, attached with a variety of sensors (Fig. 66c). Each sensor is designed for a specific application and sample type, and is connected to the MS2 meter via a simple coaxial cable. The meter displays the magnetic susceptibility value of materials when these are brought under the influence of the sensor. The MS2 meter is powered by internal rechargeable batteries. The resolution of the sensor is $2 \times 10^{-6}$ SI unit ($2 \times 10^{-7}$ CGS) on 0.1 ranges. The resolution achieved will depend on temperature drift and environmental noise. The measurements are obtained digitally using a time dependent method. These obtained results are precise and repeatable. This instrument is used to measure the bulk susceptibility of the rock during different stages of measurements. Continued monitoring of susceptibility during thermal demagnetization is very important to know the magnetic mineralogy which changes due to heating.

6.2.1.4 JR-5A Spinner Magnetometer

The Spinner Magnetometer JR-5A (Model) was used for measuring the magnetic vectors of the core specimens of 09 mafic dykes (ND, AD and PD) of KLH for various pilot and blanket studies. It is used to measure NRM of the rock specimens with high precision and was carried out in the Palaeomagnetic Laboratory, IIG, Allahabad. The sensitivity of the instrument is 2.4µA/m with rotation speed of 87.7 rps (high) and 16.7 rps (low). The accuracy of the instrument/machine is 1% ± µA/m (Fig. 66d).

6.3 ANALYTICAL TECHNIQUES

The rocks sometime have charged with secondary magnetization in addition to its NRM subsequent to their formation. These can be due to several causes such as continued effect of geomagnetic field, heating by deep burial or by physical contact with other igneous bodies, lightning strokes and weathering etc. In some cases the NRM of the rocks might be completely destroyed and only the secondary effect remained in the rocks. Thus preliminary investigation on such rocks, which possess secondary magnetization, will often lead to inconsistent results. Hence, it is necessary to study the stability of magnetization of a rock formation and remove the secondary components if present, before computing the mean remnant magnetic directions. The significant effect of demagnetization techniques for separating the characteristic remanent magnetization (ChRM) from randomly distributed NRM directions.
There are two methods which routinely used as cleaning techniques, viz. alternating magnetic field (AF) demagnetization and thermal demagnetization methods. Both the methods, the magnetic and thermal energy respectively, are used to randomize the moments of the particles carrying secondary NRM. These methods require precise control and very difficult to achieve the successful consistent results in the field. Normally, this measurement has been carried out in the laboratory after collecting the oriented samples from the field. The underlying principle of the routine cleaning techniques is based on generally lower stability of secondary magnetization relative to the acquired by the primary processes of chemical remanence and thermal-remanence. This allows the preferential removal of secondary NRM by the application of sufficient energy to overcome the magnetostatic energy of alignment within particles carrying secondary remanence, leaving them magnetically randomly oriented. In practice, the intensity of the primary component is often found decreasing, but it is the direction of the primary NRM which is usually of interest for palaeomagnetic interpretation. The intensity decrease is only important if it significantly affects the accuracy with which the surviving NRM can be measured.

6.3.1 Alternating Field Demagnetization (AF-Demagnetization)

Demagnetization in alternating fields (AF) is wholly similar, and is based on the magnetic hysteresis principle. AF demagnetization was carried out by Molspin (UK) AF demagnetizer at Palaeomagnetic Laboratory, IIG, Allahabad (Fig. 66e). The sensitivity of the instrument is 1.2V. In this magnetic cleaning process the specimens are subjected to expose to an alternating magnetic field.

AF pilot studies of the mafic dykes (ND, AD and PD) were carried out. Fourteen steps of peak AF fields (25 Oe, 50 Oe, 75 Oe, 100 Oe, 150 Oe, 200 Oe, 250 Oe, 300 Oe, 350 Oe, 400 Oe, 500 Oe, 600 Oe, 800 Oe, 1000 Oe) were applied on the pilot samples to yield the ChRM directions.

6.3.2 Thermal Demagnetization

The thermal demagnetization was carried out by MMTD-80 thermal demagnetizer (USA) (Fig. 66f) to remove secondary magnetic components in the studied samples. The procedure for thermal demagnetization involves heating of a specimen to an elevated temperature \( T_{demag} \) below the Curie temperature of the constituent ferromagnetic minerals, then cooling to room temperature in zero magnetic fields. Heating and cooling of the specimens can be made stepwise. As the specimen is heated, the relaxation time of all
contained magnetic particles is reduced exponentially. It means that the grain with low relaxation time will, when heated, easily erase the remanence. The magnetization of all grains having blocking temperature \( T_{\text{demag}} \) is randomized, as well low coercive grains during AF demagnetization.

MMTD-80 thermal demagnetizer has dual chamber for simultaneous heating and cooling of the samples from room temperature up to 700°C in the variable steps. Specimens are kept gently inside the heating chamber through a titanium sample boat. The temperature controller attached with MMTD-80 is a self-learning fuzzy logic temperature controller. Initially, representative specimens were selected and demagnetized in 15 steps (50°C, 100°C, 200°C, 300°C, 350°C, 400°C, 450°C, 500°C, 530°C, 560°C, 580°C, 600°C, 630°C, 680°C, 700°C) for pilot thermal demagnetization study.

### 6.4 MEASUREMENT OF REMANENT DIRECTION

Remanence direction (i.e., magnetization along north, east and vertical) including natural remanent magnetization (NRM) intensities were measured with JR-5A Spinner magnetometer (M/S Agico, Czech Republic) with sensitivity of 3pT. Rock specimens of defined size and shape rotate at a constant angular speed of 89.3 rev/s in the pick-up unit inside a pair of coils. The instrument takes 2-20 minutes to measure the direction and total intensity of the remanence depending upon the magnetic moment of the specimen. Adequate measurements can usually be made in some 20 minutes for magnetic moments as low as \( 5 \times 10^{-10} \) Am² (\( 5 \times 10^{-5} \) Am⁻¹ intensity for standard 2.5cm diameter \( \times \) 2.2 cm length cylinders). The measuring range of the instruments is 1.6 mA/m to 1600 mA/m and having its sensitivity \( \sim 2.4 \) µ A/m with noise in the pick-up coil is 2.4 µ A/m. The practical lower limit of NRM for routine measurements is in the region of \( 5 \times 10^{-5} \) kg⁻¹, with a measurement time of 10 to 30 minute per sample with an accuracy of direction of 5° to 10°. By spinning about three axes, two rectangular components of the projection of remanent magnetization (RM) vector into the plane perpendicular to the axes of rotation can be calculated by Fourier analysis. The total vector is determined by spinning the specimen about a second orthogonal axis, although in practice the specimen is rotated successively about three axes to obtain average values of the NRM components and reduce the effect of inhomogeneity. The total moment and its direction are then determined from the average values of X (north), Y (east) and Z (vertical).

**Calibration:** The JR-5A spinner magnetometer calibration is simple measurement of the standard, which yields the gain and phase for calculating the remanence vector components. For calibration, standard value specimen of having value 6.29 places in the
holder and measured by spinning the holder. One measurement consists of four steps in four different positions. During each step, the instrument shows the components of NRM directions based on its position in the holder. The output of the spinner magnetometer is connected with a computer and with the help of software by which magnetic moment vector in terms of Declination (D) and Inclination (I) can be calculated from the magnetization measured along three perpendicular directions i.e. X, Y and Z. Without calibration a maximum possible phase error of 1.5% could combine with the intensity error of 3.5% due to laboratory temperature changed. Thus the results measured could be differed by as much as 5% from the true values without calibration.

6.5 RESULTS OF THE PALAEO MAGNETIC STUDY

The results of the palaeomagnetic study are given below for AD, PD and ND of KLH separately. The results of average NRM, magnetic susceptibility values of the studied mafic dyke samples were also given in the table 27.

Table 2: The rock magnetic and palaeomagnetic results of the mafic dykes of AD, PD and ND

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Location</th>
<th>N</th>
<th>MS (SI)</th>
<th>NRM (A/m)</th>
<th>D</th>
<th>I</th>
<th>VGP Lat. (North)</th>
<th>VGP Long. (East)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AD</td>
<td>2</td>
<td>778</td>
<td>0.102</td>
<td>292.7</td>
<td>-37.4</td>
<td>3.82</td>
<td>295.2</td>
</tr>
<tr>
<td>2</td>
<td>PD</td>
<td>6</td>
<td>124</td>
<td>0.227</td>
<td>345</td>
<td>44</td>
<td>76.58</td>
<td>336.2</td>
</tr>
<tr>
<td>3</td>
<td>ND</td>
<td>1</td>
<td>3819</td>
<td>4.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Meta- volcanics</td>
<td>1</td>
<td>80.5</td>
<td>8.90E-04</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

N=Number of dykes; MS=magnetic Susceptibility; NRM=Natural remanent magnetization intensity; D=Mean declination; I=Mean Inclination. ND did not provide any stable D and I values and so that VGP Latitude and Longitude could not be calculated.

In the above table, metavolcanic sample from Bhimtal volcanics was collected for the comparison purpose and not used in further analytical processes. The analytical result shows MS value of 80.5 and NRM of 8.90-04 which suggest that metavolcanics cannot be used for palaeomagnetic study because of isolation of the secondary magnetization not the primary one.

6.5.1 Almora dykes (AD)

Sixteen oriented block samples were collected from AD. These samples were cored and cut to prepare nearly 30 specimens. Magnetic susceptibility was measured on all the
specimens and the average MS value was found as $778 \times 10^{-2}$ SI units. The NRM intensity was also measured on all the specimens and the NRM intensity was noticed as $1.02 \times 10^{-1}$ A/m.

6.5.1.1 AF Demagnetization result of AD

![Fig. 67](image)

The above figures show the typical behaviour of the AF demagnetizations response on the AD samples. The weak secondary magnetic component was removed by the application 50 Oe and the westward directed declination along with shallow negative inclination stable component was recovered.

6.5.1.2 Thermal Demagnetization result of AD

![Fig. 68](image)

The above figures show the typical behaviour of the AF demagnetizations response on the AD samples. The weak secondary magnetic component was removed by the application 50 Oe and the westward directed declination along with shallow negative inclination stable component was recovered.
The above figures show the thermal demagnetization spectra (Fig. 68a, b) on the representative specimen belonging to AD. As in the case of AF demagnetizations, thermal demagnetizations also revealed the primary ChRM component of westward declination with shallow negative inclinations. The secondary weak magnetic component was removed by the application of 100°C heating step. From the intensity decay diagram (Fig. 68c), it could be noticed that the intensity was dropped at the 450°C and 585°C indicating the dominance of magnetite and titatomagnetite in the AD samples.

Figures 69a-b shows the mean ChRM direction (D=292.7° and I=-37.4°; A95=7°) yielded from the AF and thermal demagnetizations on the AD. The virtual geomagnetic pole (VGP) was calculated by using the mean ChRM and the VGP was noticed at Latitude 3.82°N and Longitude 295.2°E. The calculated VGP was plotted on the apparent polar wandering path (APWP) as proposed by Vandamme et al., (1991) and the ages of AD were estimated as ca 120 Ma.

6.5.2 Pithoragarh dykes (PD)

Thirty-three oriented samples were collected from PD and prepared about 85 specimens for palaeomagnetic measurements. Magnetic susceptibility was measured on all
the specimens and the average MS value was found as $124 \times 10^{-2}$ SI units. The NRM intensity was also measured on all the specimens and the NRM intensity was noticed as $2.27 \times 10^{-1}$ A/m.

6.5.2.1 AF Demagnetization result of PD

![Images](a) Stereographic projection of Declination and inclinations, (b) Zijderfeld diagram and (c) Normalized intensity.

Fig. 70 (a) Stereographic projection of Declination and inclinations, (b) Zijderveld diagram and (c) Normalized intensity.

The above figures show the response of AF demagnetizations on the representative PD samples. A weak secondary component was removed by the application of 50 Oe. AF field and a very stable primary component was isolated in the 100-600 Oe AF. From AF demagnetizations, NNW directed declination with positive inclination was isolated as the primary remanent magnetization direction in the samples.

6.5.2.2 Thermal Demagnetizations result of PD

![Images](a) Stereographic projection of Declination and inclinations, (b) Zijderveld diagram and (c) Normalized intensity.
Fig. 71 (a) Stereographic projection of Declination and inclinations, (b) Zijderveld diagram and (c) Normalized intensity.

The above figures show the thermal demagnetization behaviour on PD samples. The secondary component was removed by the application of 150°C thermal step, and the primary component was isolated between 200°C-600°C. As in the case of AF demagnetizations, the thermal cleaning technique also isolated NNW directed primary component.

Mean ChRM:
\[ D=345.2°; I=43.6° \]
\[ A95=4.8° \]

Pitoragarh Dykes VGP
Lat: 76.58°N; 336.2°E

Fig. 72a shows the ChRM directions of PD

Fig. 72b VGP plot on APWP for the Palaeoproterozoic period (after Radhakrishna et. al., 2013)
The above figures 72a-b show the mean ChRM direction isolated from AF and thermal demagnetizations. The mean ChRM direction was found as D=345.2 and I=43.6. The VGP was calculated using this direction and the VGP was calculated as Latitude 76.58°N and Longitude 336.2°E. The calculated VGP is plotted on the APWP for the Palaeoproterozoic period (APWP proposed by Radhakrishna et al, 2013) and the ages of the Pithoragarh was estimated as ca 1000 Ma.

6.5.3 Nainital dykes (ND)

Five oriented samples were collected from ND and 45 specimens were prepared. Magnetic susceptibility was measured on all the specimens and the average MS value was found as 3818×10^-2 SI units. The NRM intensity was also measured on all the specimens and the NRM intensity was noticed as 4.01 A/m.

6.5.3.1 AF Demagnetizations result of ND

![Fig. 73](image)

(a) Stereographic projection of Declination and inclinations, (b) Zijderveld diagram and (c) Normalized intensity.

The above figures show the AF demagnetization response on the ND samples. It could be observed that there was no any grouping found from the step wise AF demagnetizations.
6.5.3.2. Thermal Demagnetizations result of ND

Fig. 74 (a) Stereographic projection of Declination and inclinations, (b) Zijderveld diagram and (c) Normalized intensity.

The above figures show the thermal demagnetization spectra on ND samples (Fig. 74a-b). As in the case of AF demagnetizations, thermal demagnetizations also could not give any stable isolation directions. It is therefore the mean ChRM values of the primary remanent magnetization have not been identified and hereby no VGP can be calculated. The thermal and AF demagnetizations failure to yield stable direction from ND could be due to the weathered or alteration nature of the mafic dyke samples evident from isolation by the secondary magnetic field.

6.6 ROCK MAGNETISM

Isothermal Remanence Magnetization (IRM) measurements were carried out on selected specimens to determine the magnetic mineralogy and their domain states. Specimens were magnetized in forward fields up to 1T and then followed by the backward fields. IRM acquisition and demagnetization curves of the representative specimens were shown in figure 75a. From the figure it can be observed that all the studied specimens’ remanences were started saturation in the forward fields of 150 to 200 mT and completely saturated at 300 mT indicating the major magnetic mineral in the samples as magnetite and titanomagnetite. Figure 75b shows the temperature dependent magnetic susceptibility (k-T curve) of the representative samples. It can be observed that the heating curve dropping to zero at 585°C (Curie point of magnetite) indicating the magnetite as the major magnetic mineral in the samples, complementing our findings from IRM curves and thermal demagnetizations.
Fig. 75a shows Isothermal Remanence Magnetization (IRM) curves of the representative samples. It shows the application of 300 mT, induced field is saturated. It indicates “Magnetite” as the major magnetic mineral in the samples.

Fig. 75b shows temperature dependent magnetic susceptibility (k-T) curves of the representative samples. Curie temperature is observed at 585°C. This also proves “Magnetite” as the major magnetic mineral in the samples.

6.7 Conclusions for palaeomagnetic study

From the detailed AF and thermal demagnetization cleaning techniques on the samples of AD and PD samples, the primary remanence magnetization directions were isolated. The AF and Thermal techniques were found equally fruitful to isolate the ChRM directions. The AD yielded a VGP as Latitude 3.82°N and Longitude 295.2°E assigning the ages for these dykes as ca 120 Ma. The PD also yielded well grouped ChRM directions
through AF and thermal demagnetizations and VGP calculated from these dykes were found as Latitude 76.58°N and Longitude 336.2°E, indicating the ages of these dykes as ca 1000 Ma. However, the ND could not provide any stable directions from the application of AF and thermal demagnetizations. It might be because of altered and weathered nature of block samples. The rock magnetic experiments consisting of IRM and k-T curves indicated that all the dyke samples contain “magnetite” as the major magnetic mineral.