Journal of Nepal Geological Society, 1995, Kathmandu, Vol. 11, Special Issue, pp. 179-195

Paleomagnetism and Petrochemistry of the Dowar Khola Volcanics, Central Nepal Sub Himalaya

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ABSTRACT

The doleritic volcanic rocks, which occur in the Sub-Himalaya in east central Nepal, are represented by metric to decimetric (in thickness) sill-like bodies at several stratigraphic levels showing concordant relationship with the predominantly red coloured sedimentary rocks of Pre-Siwalik age. Chemistry of the clinopyroxenes contained in these rocks suggests that they are poor in TiO_2 compared to the alkalic rocks and belong to non-alkalic and non-orogenic group basalts (judging from discriminant diagrams: Ti vs. Ca+Na and Ti+Cr vs. Ca). Whole rock chemical analyses on major oxides, trace-elements and REE characteristics (P_2O_5 vs. Zr and TiO_2 vs. Zr plots; rock/OIT, rock/MORB, rock/chondrite spidergrams) indicate affinity to the tholeiitic field and similarity with the within plate basalts (WPB). Spidergrams, Y/Nb (2.06-2.66) vs. Zr/Nb (12.42-13.77) plots and La/Nb (1.34-2.11) ratios for the Dowar Khola volcanics show similarity to the commonly known continental flood basalts (Snake-river plain, Parana and Deccan basalts).

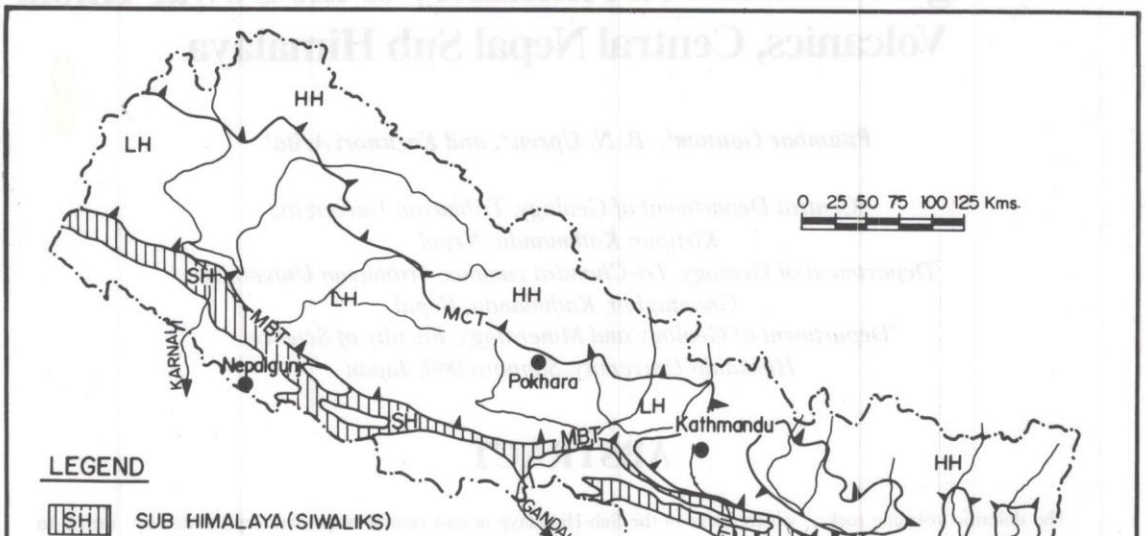
Paleomagnetic study on the volcanic rocks reveals magnetite-based characteristic remanent directions, which have NE (SW) declinations with shallow downward (upward) inclinations after tilt-correction. The best inclination estimate of the primary thermo-remanent magnetisation yields a shallow northern paleolatitude (6.4±4.3°N) of acquisition implying the most probable age to be around 45 Ma (younger and older age limits of 35 and 50-52 Ma, respectively). Primary detrital remanent magnetisation with similar orientation is preserved in the red sandstones carried out mainly by haematite and partly by magnetite as well and indicates shallow near-equatorial northern latitudinal paleoposition of the area during the deposition of the sediments. Declination anomalies amount to 35-80° relative to the present day north and increase by an additional 15° if considered with respect to the expected Middle Eocene paleodeclination for the area suggesting a significant clockwise tectonic rotation. Considering the best defined remanence directions, the volcanic episodes and the deposition of associated sedimentary rocks took place sometimes in the lower Tertiary between the Eocene and Early Oligocene.

INTRODUCTION

The present work is concerned with the field mapping, petrochemistry and paleomagnetic study of the doleritic volcanic rocks that are distributed within a narrow Sub-Himalayan (geographically) zone in east central Nepal. These volcanic rocks referred here as Dowar Khola volcanics were first reported briefly by Herail et al. (1986), who hinted their possible association with the lower Gondwana deposits. They were later reported also by Kaphle and Einfalt (1992) from the Dowar Khola section and described as basic volcanic rocks having concordant field relationship with the host clastic sedimentary rocks. The latter were interpreted to belong to the Lower Siwaliks, and hence a post mid-Miocene age volcanic activity was suggested.

BRIEF GEOLOGICAL OUTLINE

The area studied lies geographically within the Sub-Himalayan belt to the north of the Marin Khola (a tributary of Bagmati river in its middle reaches). Tectonically, it lies in between the Main Dun Thrust (Herail et al. 1986) and the Main Boundary thrust (MBT) (Fig. 1a). Although, along the Himalaya, the zone lying to the south of the MBT is represented by thick sequence of cyclic fluviatile molasse sediments a



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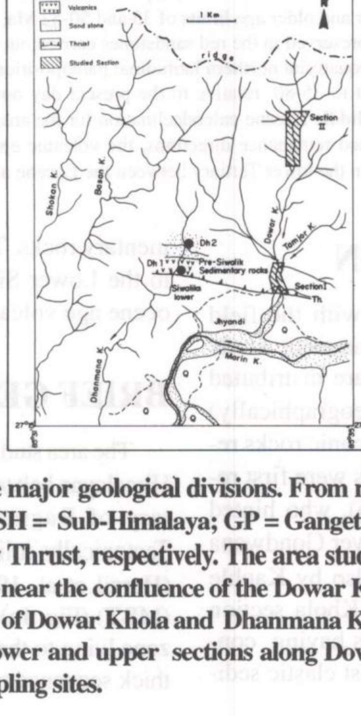


Fig. 1 (a) Map of Nepal showing the major geological divisions. From north to south, they are: HH = Higher Himalaya; LH = Lesser Himalaya; SH = Sub-Himalaya; GP = Gangetic Plain. MCT and MBT denote Main Central Thrust and Main Boundary Thrust, respectively. The area studied lies in the vicinity of Jhyandi (27° 16.2' N, 85°33.5' E), a village located near the confluence of the Dowar Khola and Marin Khola.
(b) Sketch map showing the location of Dowar Khola and Dhanmana Khola sections in the vicinity of Jhyandi village, Sindhuli District. Sampled lower and upper sections along Dowar Khola are indicated. Solid circles along the Dhanmana Khola are sampling sites.

of mid-Miocene to Lower Pleistocene age belonging to the Siwalik Group, this area is characterized by the presence of pre-Siwalik age rocks belonging to the Lesser Himalaya.

Herail et al. (1986) described the occurrence of "substratum outcrops", represented by red and green sandstones/shales correlatable to Dharamsala-Murrees and underlying Gondwana beds including the dolerites in this area. These rocks occur within one or more thrust slices sandwiched between the Siwalik rock units.

Kaphle and Einfalt (1992) studied the doleritic volcanic rocks occurring along the Dowar Khola. They described these volcanics to have concordant relationship with the host clastic sedimentary rocks, belonging to the Lower Siwaliks, and hence inferred a very young i.e. post mid-Miocene volcanic activity within the Siwaliks in this area.

The detailed geologic route mapping along the Dowar Khola by two of us (PG and BNU) has shown the occurrence of the volcanic rocks in two sections about 2 km apart from each other. The lower section lies near the Jhyandi village whereas the upper section lies in the middle reaches of the Dowar Khola. (Fig. 1b). In the lower section, the volcanic rocks occur at two levels, being at least 150 m thick at each level (Fig. 2a). In the upper section, they occur at 5 different levels, the thickness at each level ranging between 15 and 120 m. In all the cases, they have sharp contact with the host rocks (Fig. 2b). In the upper section, the host rocks are represented by white, light-green to red-purple quartzose sandstones and occasionally micaceous haematitic red sandstones and red-purple to gray shales. In general, they exhibit 40-55° dips towards the North. In the lower section, the host rocks are light-gray and light purple sandstones with shale intercalations. These host rocks are distinctly more indurated than the Siwalik rocks and exhibit low-grade metamorphic effects. Field observations suggest that the loose, variegated mud-rocks underlying the volcanics with a thrust contact at the lower level in the lower section (Fig. 2a) belong to the Siwalik group. Similarly, the light green sandstones overlying the red nodular haematitic chocolate-coloured sandstones and shales above the uppermost volcanic layer in the upper section, also with a thrust contact, belong to the Siwaliks. Hence, the rock sequence in between the thrusts including the volcanics constitutes a thrust package, as suggested by Herail and Mascle (1980) (see in Herail et al. 1986). The rocks are therefore of pre-Siwalik age. Further, an additional thrust (a shear zone represented by intensely deformed gray and black shales) occurs in between the lower and upper sections of Dowar Khola. Further to the west, in the Dhanmana Khola, however, the volcanic rocks occur only at one level within a zone lithologically correlatable to the lower section of the Dowar Khola.

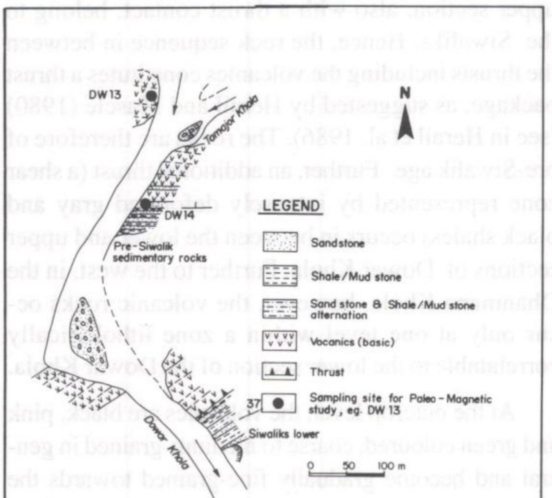
At the outcrop level, the volcanics are black, pink and green coloured, coarse to medium-grained in general and become gradually fine-grained towards the contact with the host rocks. They commonly exhibit vesicular and amygdaloidal structures. At places, chilled margins with development of glass are found.

PALEOMAGNETISM

Palaeomagnetic investigation was carried out on both the volcanic and sedimentary rocks sampled at 17 sites (3 samples/1 site on Siwalik Group, 44 samples/9 sites on volcanics and 29 samples/7 site on red-coloured sediments) collected from the Dowar Khola and Dhanmana Khola sections (Gautam, 1993). Sampling sites are shown in Fig. 2(a) and (b) and details are given in Table 1. Remanent magnetisation measurements were carried out by using a ring-core spinner magnetometer (Natsuhara SMM-85; noise level = about 0.1 mA/m). Standard progressive thermal cleaning (max. heating temperature: 600° C for volcanic rocks and 685° C for sedimentary rocks) and stepwise alternating field (AF) demagnetisations (max. peak alternating field employed: 100 mT) were also performed. All the magnetic measurements were carried out at Tribhuvan University.

NATURAL REMANENT MAGNETISATION (NRM) AND DEMAGNETISATION BEHAVIOUR

NRM intensities of the volcanic rocks range between n.10^1 and n.10^2 mA/m while those for the red a



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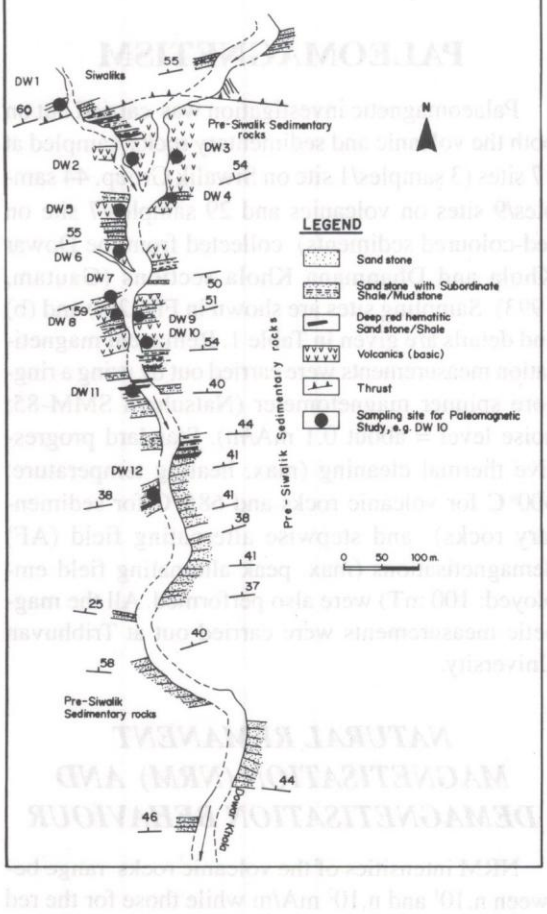

beds are lower by an order of magnitude (Table 1). The Siwalik rock samples have still low intensities of about 0.1 mA/m order. Both AF and thermal demagnetisation methods successfully reveal the stable remanence preserved in the volcanic rocks (Figs. 3a and 3b). The unblocking temperatures in the volcanic rocks are mostly between 400 and 600° C suggesting magnetite to be the remanence carrier whereas its grain size varies as indicated by differing coercivity spectra (Median destructive fields: <20 mT to 50 mT). Surprisingly low coercivity (MDF = 10 mT) was exhibited by specimens from site DW10 (> 90% of the NRM lost below 20 mT) and the remanence showed complex multicomponent nature. Single-component behaviour was exhibited by specimens from sites DW2, DW3 and DW5. In many specimens, viscous soft components of recent field and unknown origin are commonly present along with stable directions with NE (SW) declinations and shallow downward (upward) inclinations after tilt-correction. For most redbed specimens, alternating field is not effective because of high coercivity of the major part of the remanence resting on haematite. Only a part of the remanence, probably residing on magnetite, is removed during AF cleaning.

Thermal demagnetisation confirms that both magnetite and haematite carry the remanence (unblocking temperatures: 400-680° C and both low and high coercivities) (Fig. 3a and 3b). The characteristic remanence mainly carried by haematite has ENE (SW) declinations and shallow downward (upward) inclinations after tilt correction, as it was found in the volcanic rocks.

MAGNETIC DIRECTIONS

Summary of directions estimated after demagnetisation is presented in Table 2. Those mean directions which show affinity towards present day field direction in the study area before tilt correction are designated as *Recent* viscous directions. Those clearly differing from the present day field have been

Fig. 2 (a) Route map along the lower part of the Dowar Khola section (section I, Fig. 1) with locations of sampling sites for paleomagnetic study. (b) Route map along the upper part of the Dowar Khola section (section II, Fig. 1) with sampling locations

Table 1 Natural remanent magnetisation intensities and directions with sampling details

Site Index	N(n)	Jn, in 10^{-4} A/m	Mean NRM Direction Decl (°)	Incl (°)	k	α_{95} (°)	Lithology	Bedding Strike/Dip
Dowar Khola Sites (Upper Section):								
DW 1*	9 (3)	2.8	96	70	3	33.0	ss., green	256,57N
DW 2	**8 (7)**	**2722.5**	**224**	**-66**	**2**	**56.5**	**basic volc.**	**(255,55N)**
DW 3	**10 (7)**	**9956.0**	**245**	**-32**	**60**	**6.3**	**„ „**	**(255,55N)**
DW 4	5 (4)	194.9	235	-35	9	26.7	sh.,red sandy	255,55N
DW 5	**8 (7)**	**2257.6**	**78**	**19**	**4**	**30.1**	**basic volc.**	**(255,55N)**
DW 6	**4 (3)**	**4212.5**	**24**	**55**	**17**	**23.2**	**„ „**	**(255,55N)**
DW 7	7 (4)	72.8	64	-11	32	10.8	ss., red	72,73S
DW 8	**5 (4)**	**2020.0**	**67**	**1**	**2**	**73.9**	**basic volc.**	**(255,52N?)**
DW 9	5 (4)	47.7	123	-14	15	20.7	ss., red	255,52N
DW10	**11 (7)**	**5780.0**	**112**	**-2**	**76**	**5.3**	**basic volc.**	**(260,56N)**
DW11	6 (4)	252.4	263	-4	4	41.2	sh., red mic.	255,53N
DW12	11 (7)	27.5	135	13	2	44.1	ss., red lam.	255,42N
Dowar Khola Sites (Lower Section):								
DW13	**3 (3)**	**5453.3**	**338**	**58**	**74**	**14.4**	**basic volc.**	**??**
DW14	**3 (2)**	**227.3**	**40**	**41**	**118**	**11.4**	**basic volc.**	**(280,50N)**
DW14	4 (2)	560.0	71	43	960	3.0	ss., red mic.	280,50N
Dhanmana Khola Sites:								
Dh 1	**4 (4)**	**2500.0**	**315**	**53**	**66**	**11.4**	**basic volc.**	**(278,66N)**
Dh 2	6 (4)	63.9	74	10	58	8.8	ss., red.hmt.	83,73S

Symbols and abbreviations: N: no. of specimens; n: no. of samples; Jn : mean intensity; Decl: declination; Incl: inclination; k and α_{95} are the estimates of the precision parameter and radius of 95% confidence circle, respectively, calculated using Fisher (1953) statistics (unit weight to specimens; directions are in situ);
sh. = shale, ss. = sandstone; hmt.= hematitic, volc. = volcanic rock, mic. = micaceous, lam. = laminated.
The bedding attitudes for volcanic rock sites were obtained from adjacent sedimentary beds and hence are placed within brackets.
* this site only belongs to Siwalik Group (Lower ?) sediments, while all other sites are of Pre-Siwaliks age.
Volcanic rock sites are shown in bold.

corrected for bedding tilt. Directions with reasonably good statistics (α_{95} < about 15°) have been used for paleolatitude estimation. Because of the very low NRM intensity (in the order of 0.1 mA/m: comparable to the noise level of the spinner magnetometer employed) of the rocks from Siwalik site no characteristic remanence could be isolated. Three sites on volcanics show almost complete overprinting by viscous components of recent field origin, while one site shows soft significant *in situ* remanence with easterly declination and nearly horizontal inclination of unknown origin. The mean directions obtained from individual sites before and after tilt correction are shown in Fig. 4 (volcanics) and Fig. 5 (sedimentary rocks).

IMPLICATION OF THE CHARACTERISTIC REMANENCE TO THE AGE

The characteristic remanence in both the volcanics and sedimentary rocks is of dual polarity, has similar orientations and shows better grouping

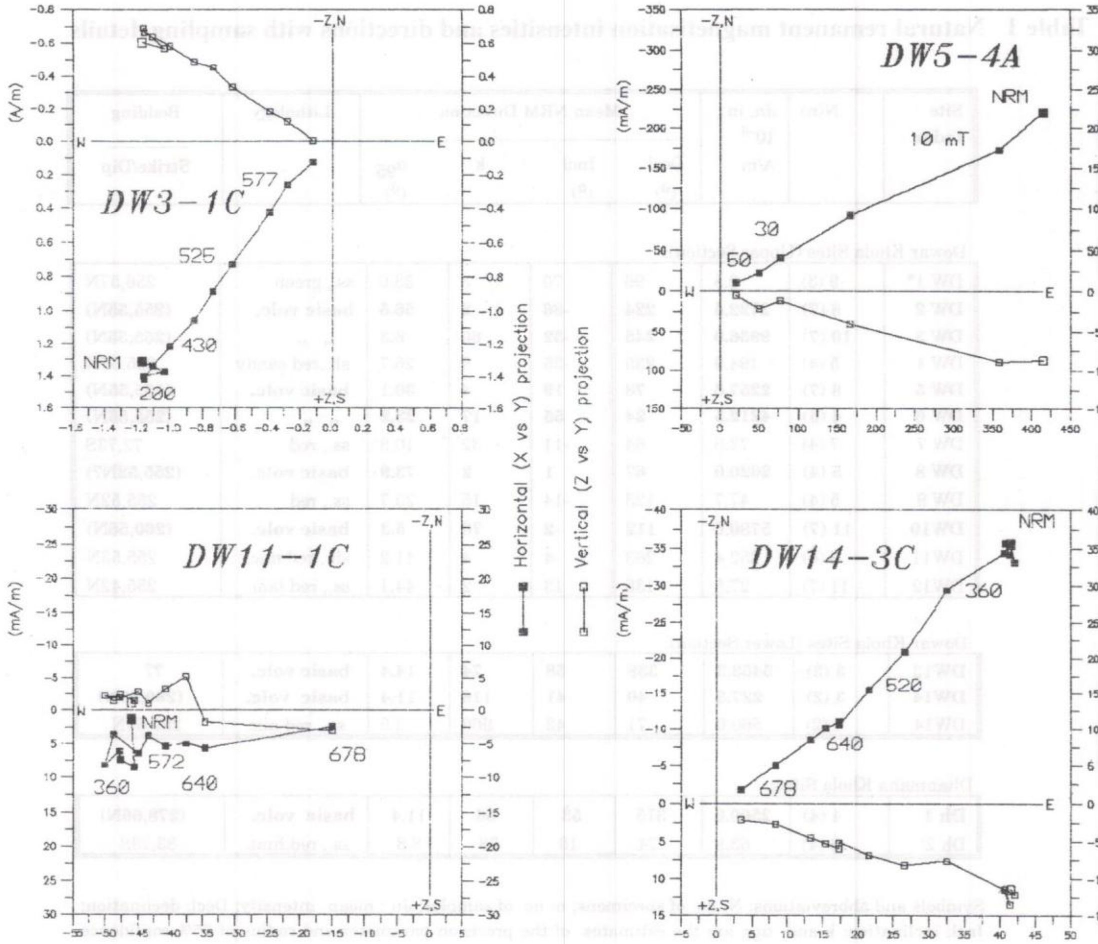

Fig. 3(a) Orthogonal vector plots showing demagnetisation behaviour of representative specimens (basic volcanic rocks: DW3-1C & DW5-4A; red sandstones: DW11-1C & DW14-3C) upon magnetic cleaning (thermal: DW3-1C, DW11-1C & DW14-3C; alternating field: DW5-4A). Numbers besides the projection points indicate peak demagnetisation temperatures (° C) or fields (mT). Directions are corrected for bedding.

after tilt-correction. Hence, this remanence is interpreted as of primary origin. The best estimate of mean direction from the volcanics is obtained by combining samples from two sites DW2 and DW3 (uppermost flow, upper section of Dowar Khola):

$$N = 12, D = 216.3^{\circ}, I = -12.1^{\circ}, k = 29, \alpha_{95} = 8.3^{\circ}$$

This direction is interpreted as primary thermoremanent magnetisation of reverse polarity. A shallow northern paleolatitude 6.4±3°N for the Dowar Khola area during the remanence acquisition is suggested. This paleolatitude indicates that the rocks acquired the remanence around 45 Ma (older and younger limits: 50-52 and 35 Ma, respectively) if compared with the expected paleolatitude pattern as a function of the time based on Indian apparent polar wander path (APWP) data (e.g. Klootwijk et al. 1985; Patriat and Achache 1984).

Well-defined inclinations of the characteristic remanence in red sediments from certain sites (DW7, DW14 and Dh 2) also yield similar paleolatitudes. Directions from most of the redbed sites, however, poorly defined in majority of cases owing to rather

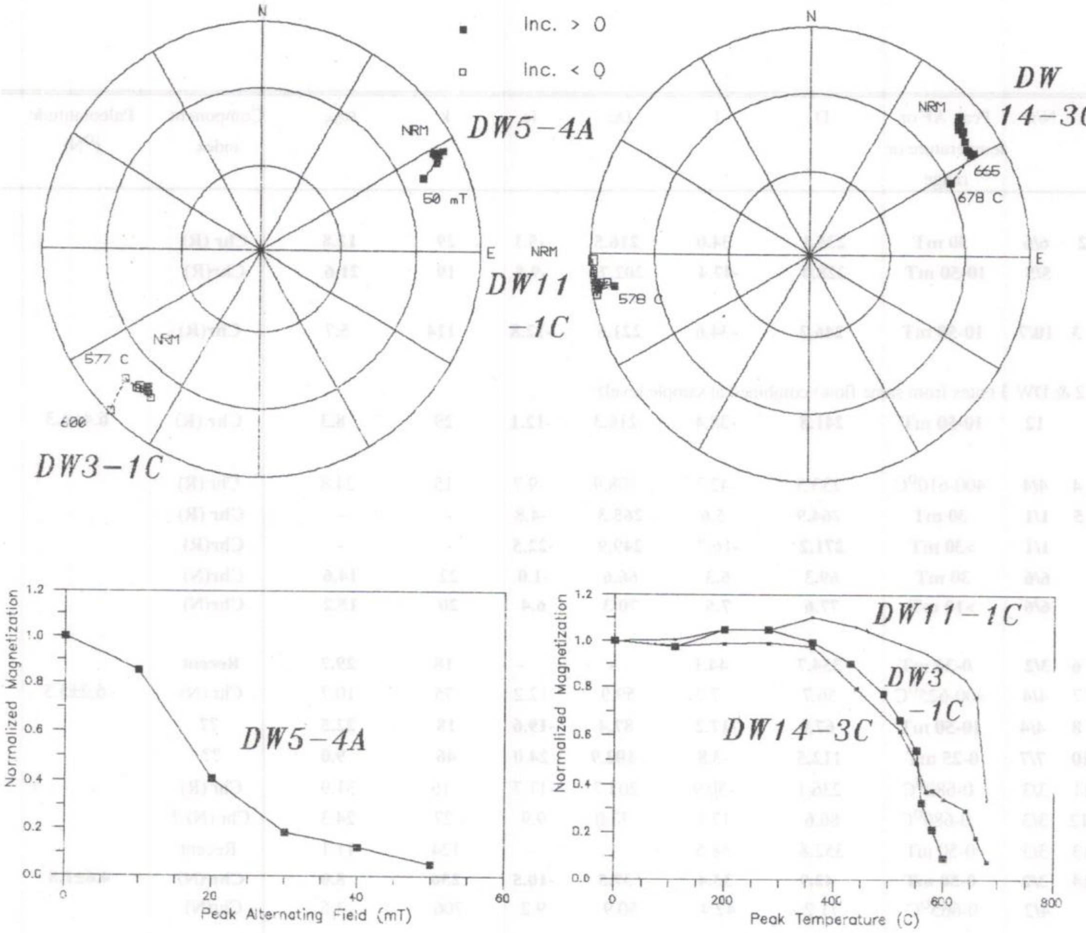

Fig. 3(b) Equal-area projection diagrams showing the changes in resultant magnetisation vectors during magnetic cleaning and intensity response curves for specimens mentioned in Fig. 3(a). Directions are corrected for bedding.

weak magnetisation intensities. This may be partly due to the contribution of post-depositional remanence and/or the inclination shallowing of the remanence recorded by the haematite grains so well established in the Siwalik rocks (see Gautam and Appel, 1994).

Declinations of the characteristic remanence are deviated clockwise relative to the present day north by about 35-80° and by an additional 15° if compared with respect to the expected Middle Eocene paleodeclination for the area derived from the Indian apparent polar wander path. It therefore seems that significant clockwise rotation has taken place.

Based on the best defined remanence directions, the most probable age for the deposition of the redbeds and the emplacement of volcanic rocks should be sometimes between the Eocene and Early Oligocene times.

PETROGRAPHY AND PETROCHEMISTRY

Under the microscope, the volcanic rock shows a variety of textures. The coarse-grained rocks exhibit intergranular doleritic (ophitic to subophitic) textures (Fig. 6a), whereas the fine-grained varieties show intersertal texture with plenty of opaques and

Table 2 Results of demagnetisation

Site	N/n	Peak AF or temperature or range	D	I	Dc	Ic	k	α_{95}	Component index	Paleolatitude (^{o}N)
DW 2	**6/6**	**30 mT**	**235.1**	**34.0**	**216.5**	**-5.1**	**29**	**12.8**	**Chr (R)**	
	5/5	**10-50 mT**	**228.0**	**-47.4**	**202.7**	**-9.8**	**19**	**21.6**	**Chr(R)**	
DW 3	**10/7**	**10-50 mT**	**246.2**	**-34.6**	**221.5**	**-12.8**	**114**	**5.7**	**Chr(R)**	
(DW 2 & DW 3 (sites from same flow) combined at sample level):										
	12	**10-50 mT**	**241.8**	**-38.4**	**216.3**	**-12.1**	**29**	**8.3**	**Chr (R)**	**6.4±4.3**
DW 4	4/4	400-610^{o}C	233.5	-42.7	208.9	-9.7	15	24.8	Chr (R)	
DW 5	**1/1**	**30 mT**	**264.9**	**5.6**	**265.3**	**-4.8**	**-**	**-**	**Chr (R)**	
	1/1	**>30 mT**	**271.2**	**-16.7**	**249.9**	**-22.5**	**-**	**-**	**Chr(R)**	
	6/6	**30 mT**	**69.3**	**6.3**	**66.6**	**-1.0**	**22**	**14.6**	**Chr(N)**	
	6/6	**>10 mT**	**77.6**	**7.5**	**70.3**	**6.4**	**20**	**15.2**	**Chr(N)**	
DW 6	**3/2**	**0-30 mT**	**354.7**	**44.1**	**-**	**-**	**18**	**29.7**	**Recent**	
DW 7	4/4	400-625^{o}C	56.7	-7.7	59.9	12.2	75	10.7	Chr (N)	6.2±5.5
DW 8	**4/4**	**10-50 mT**	**67.9**	**-17.2**	**87.4**	**-19.6**	**18**	**22.5**	**??**	
DW10	**7/7**	**0-25 mT**	**112.5**	**-3.8**	**102.9**	**24.0**	**46**	**9.0**	**??**	
DW11	3/3	0-680^{o}C	236.1	-50.9	203.7	-17.7	16	31.9	Chr (R)	
DW12	3/3	0-680^{o}C	86.6	17.1	77.0	9.9	27	24.3	Chr (N) ?	
DW13	3/3	0-50 mT	352.8	58.5	-	-	124	11.1	Recent	
DW14	**3/2**	**0-50 mT**	**42.9**	**33.4**	**37.5**	**-10.5**	**236**	**8.0**	**Chr (N)**	**4.6±1.8**
	4/2	0-665^{o}C	71.2	42.4	50.9	9.2	706	3.5	Chr(N)	
Dh 1	**4(4)**	**10-50 mT**	**320.2**	**56.1**	**-**	**-**	**19**	**21.8**	**Recent**	
Dh 2	4(4)	100-665^{o}C	72.3	7.1	75.9	10.7	140	7.8	Chr (N)	5.4±4.0

Note: N and n denote the number of specimens and samples, respectively. Calculation of mean and statistical parameters was done giving unit weight to sample except for site DW14 for which unit weight was given to specimen. The ranges of temperatures or AF in column 3 are generalized figures from all specimens within the site and may vary at a specimen scale. D and I are *in situ* declination and inclination, whereas Dc and Ic are *tilt-corrected* declination and inclination. In the last column, the abbreviations are: Chr = characteristic; Recent = recent field component; N = normal; R = reverse; ?? = unknown origin. Paleolatitude is derived from only well-defined (α_{95} < about 15^{o}) tilt-corrected characteristic directions. Uncertainty of the paleo- latitude is calculated as $\alpha_{95}(1+3\cos^2 p_0)/2$ where p_0 is the paleocolatitude.

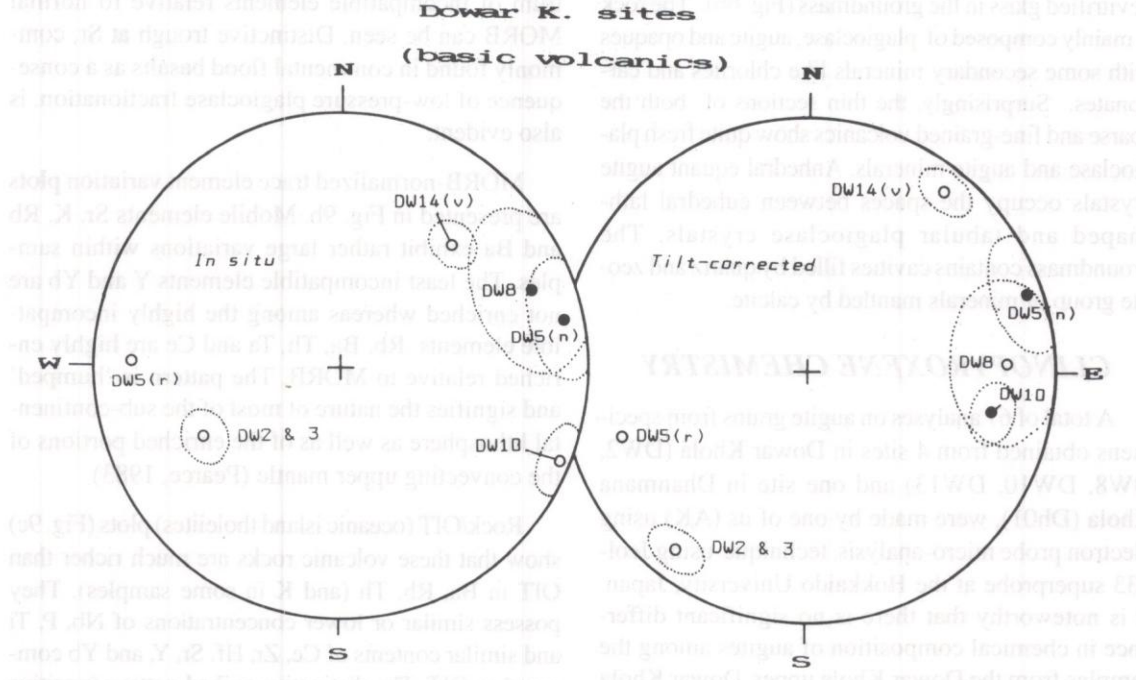

Fig. 4 Equal-area projections of the mean directions at individual sites in Dowar Khola volcanic rocks. Mean directions (solid circle - downward inclination, open circle - upward inclination) are provided with the projection of the ellipses of circle of 95% confidence as represented by the dotted lines. For data refer to Table 2. Directions from Sites DW2 and DW3 were combined at sample level.

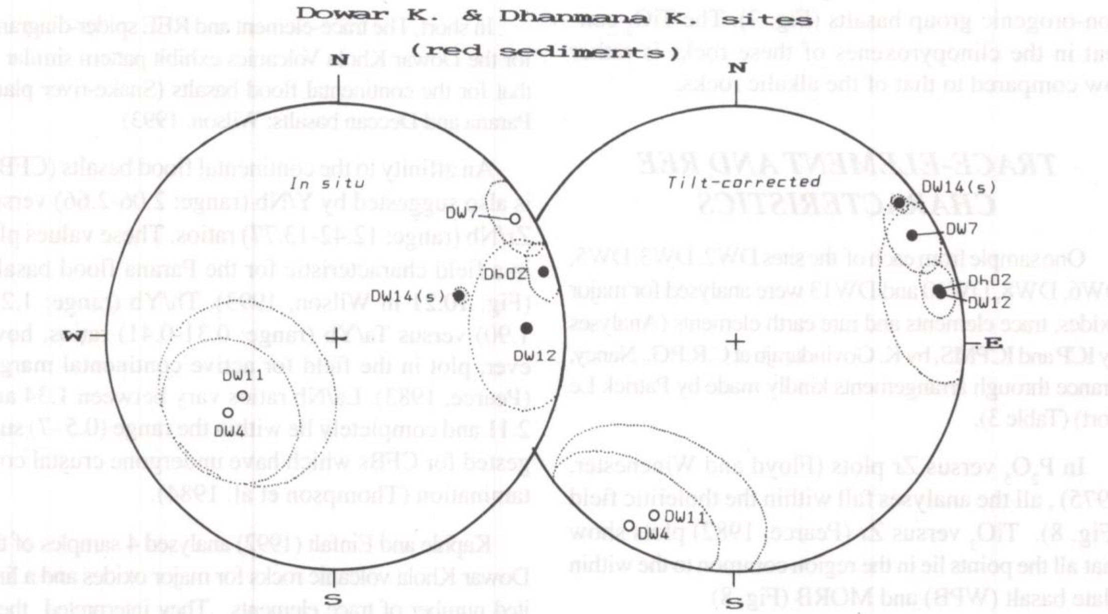

Fig. 5 Equal-area projections of the mean directions obtained from the red sedimentary rocks at individual sites. Other conventions as in Fig. 4

devitrified glass in the groundmass (Fig. 6b). The rock is mainly composed of plagioclase, augite and opaques with some secondary minerals like chlorites and carbonates. Surprisingly, the thin sections of both the coarse and fine-grained volcanics show quite fresh plagioclase and augite minerals. Anhedral equant augite crystals occupy the spaces between euhedral lath-shaped and tabular plagioclase crystals. The groundmass contains cavities filled by quartz and zeolite group of minerals mantled by calcite.

CLINOPYROXENE CHEMISTRY

A total of 67 analyses on augite grains from specimens obtained from 4 sites in Dowar Khola (DW2, DW8, DW10, DW13) and one site in Dhanmana Khola (Dh01), were made by one of us (AK) using electron probe micro-analysis technique using Jeol-733 superprobe at the Hokkaido University, Japan. It is noteworthy that there is no significant difference in chemical composition of augites among the samples from the Dowar Khola upper, Dowar Khola lower, and the Dhanmana Khola sections.

The discrimination diagrams (Ti vs. Ca+Na and Ti+Cr vs. Ca: Leterrier et al. 1982), show that these doleritic rocks belong to the non-alkalic and non-orogenic group basalts (Fig. 7). The TiO_2 content in the clinopyroxenes of these rocks is rather low compared to that of the alkalic rocks.

TRACE-ELEMENT AND REE CHARACTERISTICS

One sample from each of the sites DW2, DW3, DW5, DW6, DW8, DW10 and DW13 were analysed for major oxides, trace elements and rare earth elements (Analyses by ICP and ICPMS, by K. Govindaraju at C.R.P.G., Nancy, France through arrangements kindly made by Patrick Le Fort) (Table 3).

In P_2O_5 versus Zr plots (Floyd and Winchester, 1975) , all the analyses fall within the tholeiitic field (Fig. 8). TiO_2 versus Zr (Pearce, 1982) plots show that all the points lie in the region common to the within plate basalt (WPB) and MORB (Fig. 8)

Fig. 9a shows chondrite normalized spidergrams (Thompson et al. 1984). Enrichment in whole spectrum of incompatible elements relative to normal MORB can be seen. Distinctive trough at Sr, commonly found in continental flood basalts as a consequence of low-pressure plagioclase fractionation, is also evident.

MORB-normalized trace element variation plots are presented in Fig. 9b. Mobile elements Sr, K, Rb and Ba exhibit rather large variations within samples. The least incompatible elements Y and Yb are not enriched whereas among the highly incompatible elements Rb, Ba, Th, Ta and Ce are highly enriched relative to MORB. The pattern is 'humped' and signifies the nature of most of the sub-continental lithosphere as well as of the enriched portions of the convecting upper mantle (Pearce, 1983)

Rock/OIT (oceanic island tholeiites) plots (Fig. 9c) show that these volcanic rocks are much richer than OIT in Ba, Rb, Th (and K in some samples). They possess similar or lower concentrations of Nb, P, Ti and similar contents of Ce, Zr, Hf, Sr, Y, and Yb compared to OIT. The distinctive spiked pattern (positive spikes of Rb, Ba, Th, Ce and negative spikes of Nb, Ti and P) may be a consequence of crustal contamination. Rock/chondrite rare earth element (REE) patterns show enrichment in light REE (Fig. 10).

In short, The trace-element and REE spider-diagrams for the Dowar Khola Volcanics exhibit pattern similar to that for the continental flood basalts (Snake-river plain, Parana and Deccan basalts: Wilson, 1993)

An affinity to the continental flood basalts (CFBs) is also suggested by Y/Nb (range: 2.06-2.66) versus Zr/Nb (range: 12.42-13.77) ratios. These values plot in a field characteristic for the Parana flood basalts (Fig. 10.21 in Wilson, 1993). Th/Yb (range: 1.23-1.90) versus Ta/Yb (range: 0.31-0.41) ratios, however, plot in the field for active continental margin (Pearce, 1983). La/Nb ratios vary between 1.34 and 2.11 and completely lie within the range (0.5 -7) suggested for CFBs which have undergone crustal contamination (Thompson et al. 1984).

Kaphle and Einfalt (1992) analysed 4 samples of the Dowar Khola volcanic rocks for major oxides and a limited number of trace elements. They interpreted these volcanic rocks as olivine tholeiitic to quartz tholeiitic basalt having alkaline affiliation and within plate origin.

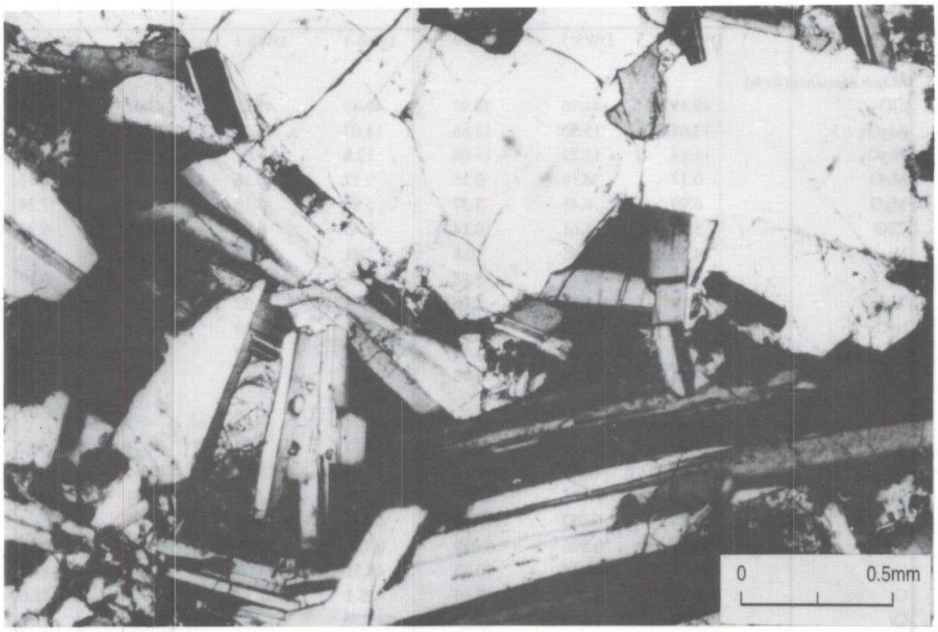

Fig. 6a Coarse grained volcanic rock (Sample No. DW10) from the upper section, Dowar Khola. Note the fresh plagioclase feldspars (p) with large crystals of clinopyroxene.

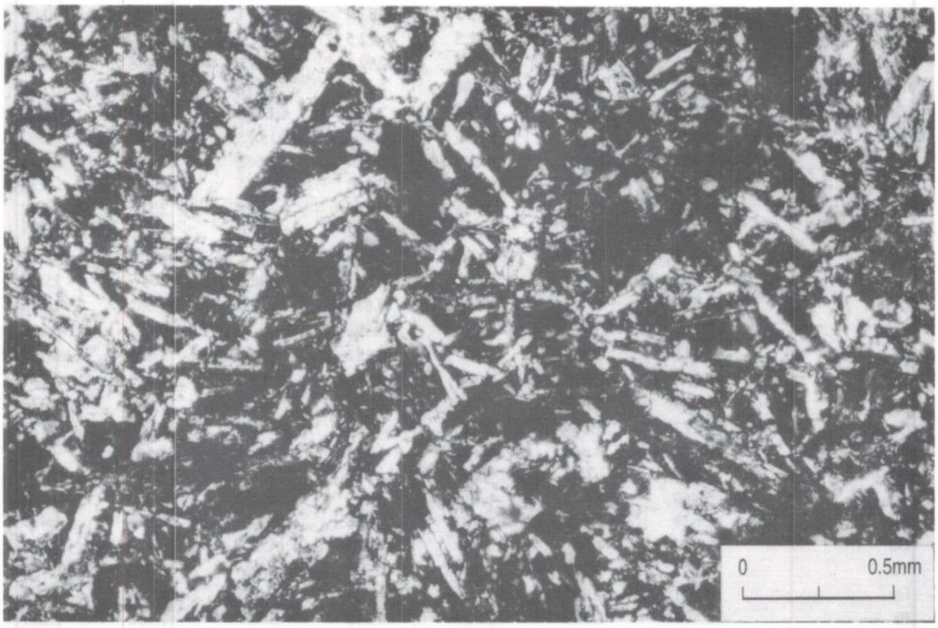

Fig. 6b Fine grained volcanic rock (Sample No. DW2-5) from the lower section, Dowar Khola. Note laths of plagioclase embedded in a fine grained matrix of clinopyroxene, opaque is glass.

Table 3 Chemical composition of volcanic rock samples from Dowar Khola

	DW2-6	DW3-3	DW5-4	DW6-1	DW8-1	DW10-4	DW13-1
Major elements (wt%)							
SiO_2	49.19	44.96	38.97	49.49	47.78	49.62	45.17
Al_2O_3	13.68	15.56	13.66	14.07	13.47	14.28	14.45
Fe_2O_3	11.88	13.22	11.08	12.8	12.1	13.25	12.43
MnO	0.17	0.16	0.15	0.17	0.16	0.17	0.15
MgO	6.99	6.41	5.37	5.89	5.16	6	7.24
CaO	5.58	4.61	10.14	9.45	6.99	10.19	6.37
Na_2O	4.56	5.35	0.8	2.11	3.3	2.2	4.63
K_2O	1.21	0.12	5.58	0.6	1.48	0.61	0.19
TiO_2	1.9	1.74	2.06	1.74	2.02	1.7	1.6
P_2O_5	0.21	0.23	0.26	0.21	0.23	0.21	0.21
PF	3.98	7.43	11.69	3.11	7.12	1.57	7.32
Total	99.34	99.79	99.76	99.64	99.81	99.8	99.76
Trace elements and REE (ppm)							
As	1.272	5.236	2.903	57.37		0.521	2.962
Ba	316.9	97.35	400.5	174.1	233.8	192.6	431.2
Be	1.03	1.625	1.761	0.727	1.539	0.884	1.442
Bi	0.128	0.033	0.099	0.013	0.008	0.027	1E-04
Cd	0.246	0.596	0.099	0.166	0.118	0.192	0.283
Co	39.07	44.37	30.35	40.51	44.05	44.53	41.68
Cr	210.6	332.5	67.15	127.1	67.32	163.6	322.6
Cs	1.024	1.308	2.295	1.276	2.182	2.561	1.78
Cu	35.33	104.5	119.3	51.63	69.88	52.93	98.7
Ga	21.87	20.54	20.91	20.48	21.28	22.01	19.81
Hf	4.213	3.734	4.483	3.424	4.136	3.52	3.601
Nb	12.88	11.37	11.97	9.321	11.34	9.823	11.03
Ni	82.32	147.4	45.94	61	56.5	76.49	147.9
Pb	5.175	12.66	7.715	4.306	28.92	5.108	8.243
Rb	30.35	11.94	73.95	18.19	53.71	20.03	10.63
Sc	21.2	21.4	22.5	22.5	21.5	22.7	20.8
Sr	169.8	114.1	46.11	239.1	166.5	253	102.8
Ta	0.97	0.836	0.909	0.689	0.838	0.727	0.835
Th	4.483	3.312	3.889	2.723	3.744	2.851	3.099
Tl	0.881	1.115	0.636	0.468	1.073	0.483	0.602
U	0.982	0.678	0.725	0.524	0.688	0.614	0.593
W	0.317	0.468	0.322	0.208	0.285	0.286	0.38
Y	26.52	25.11	31.83	23.88	26.28	25.05	23.77
Zn	105	110.9	274.9	107.2	141.6	120.6	108.4
Zr	161.9	141.3	163.7	124.1	156.2	130	138.3
V	311	273	307.5	301.2	306.9	304.9	258.2
Mo	0.531	1.042	0.872	0.833	1.366	1.061	1.016
Sb	0.147	0.171	0.213	0.095	0.22	0.092	0.138
Sn	1.545	1.261	1.307	0.897	1.307	2.805	1.308
Ho	1.037	0.975	1.205	0.934	1.04	1.012	0.938
La	17.29	16.71	25.3	16.24	21.61	17.09	15.13
Ce	43.22	39.15	50.86	35.85	46.7	37.99	36.28
Pr	5.408	4.843	5.855	4.31	5.54	4.644	4.629
Nd	23.83	21.3	25.96	19.25	24.9	19.64	20.45
Sm	5.469	5.077	6.013	4.352	5.493	4.698	4.673
Eu	1.634	1.546	1.599	1.458	1.747	1.516	1.489
Gd	5.059	4.547	5.603	4.042	4.873	4.408	4.278
Tb	0.817	0.772	0.966	0.718	0.826	0.775	0.719
Dy	4.904	4.585	5.69	4.285	4.76	4.704	4.335
Er	2.498	2.352	2.809	2.216	2.461	2.368	2.227
Tm	0.369	0.328	0.407	0.331	0.354	0.34	0.325
Yb	2.361	2.166	2.621	2.156	2.426	2.309	2.147
Lu	0.338	0.307	0.373	0.322	0.35	0.342	0.336

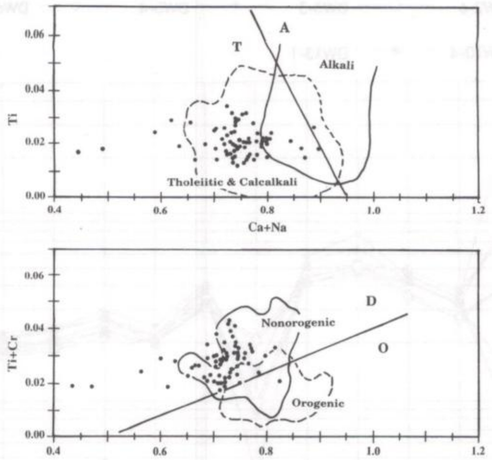

Fig. 7 Discrimination diagrams for augite phenocrysts from the volcanic rock samples to show the magmatic affinity. Compositional fields (T: 92% cpx from tholeiitic and calcalkali basalts; A: 86% Cpx from alkali basalts; D: 81% Cpx from non-orogenic tholeiites; O: 80% Cpx from orogenic basalts) after Leterrier et al. (1982)

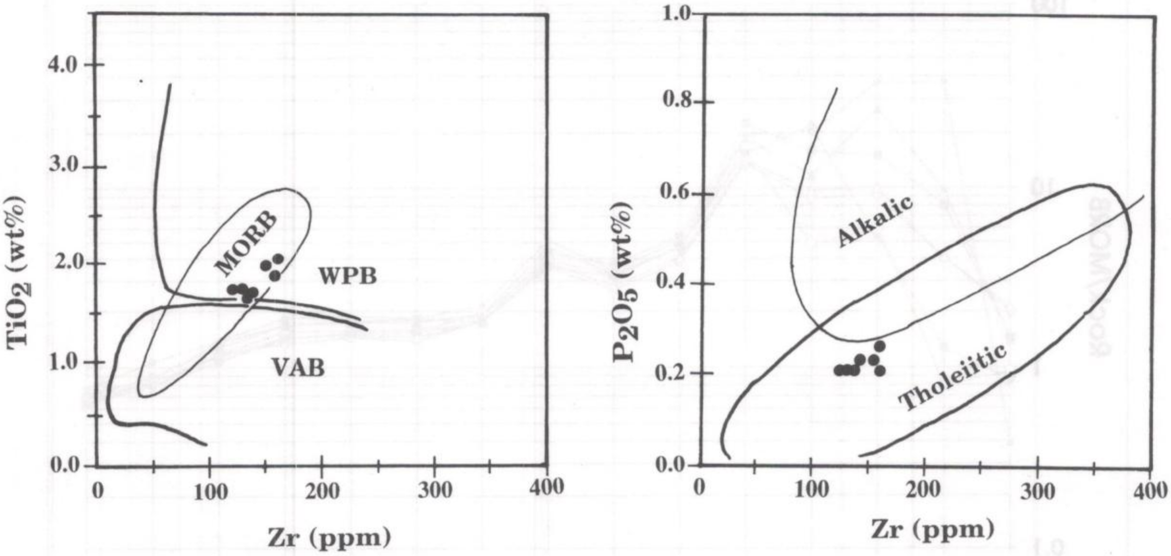

Fig. 8 Diagrams showing variation of selected major elements in the volcanic rock samples. MORB (mid-ocean ridge basalts), VAB (volcanic arc basalts) and WPB (within plate basalts) compositional fields in TiO_2 vs. Zr diagram after Pierce (1982). Alkalic and tholeiitic fields in P_2O_5 vs Zr diagram after Floyd and Winchester (1975)

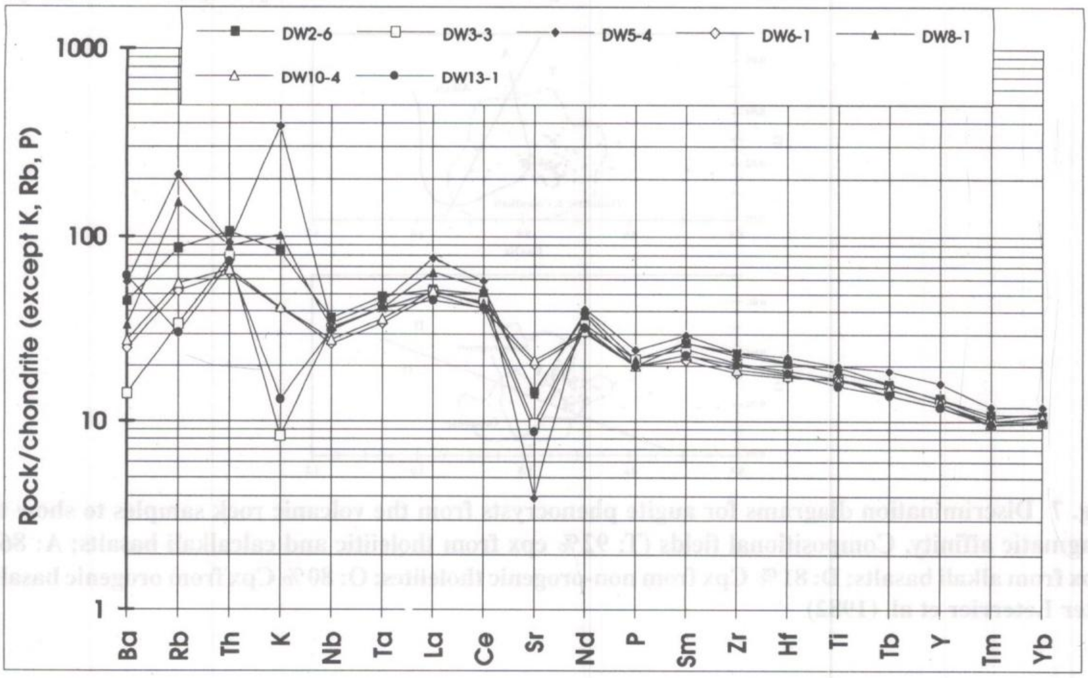

Fig. 9(a) Mantle-normalized trace element diagrams for Dowar Khola volcanic rock samples. Normalisation factors from Thompson et al. (1984)

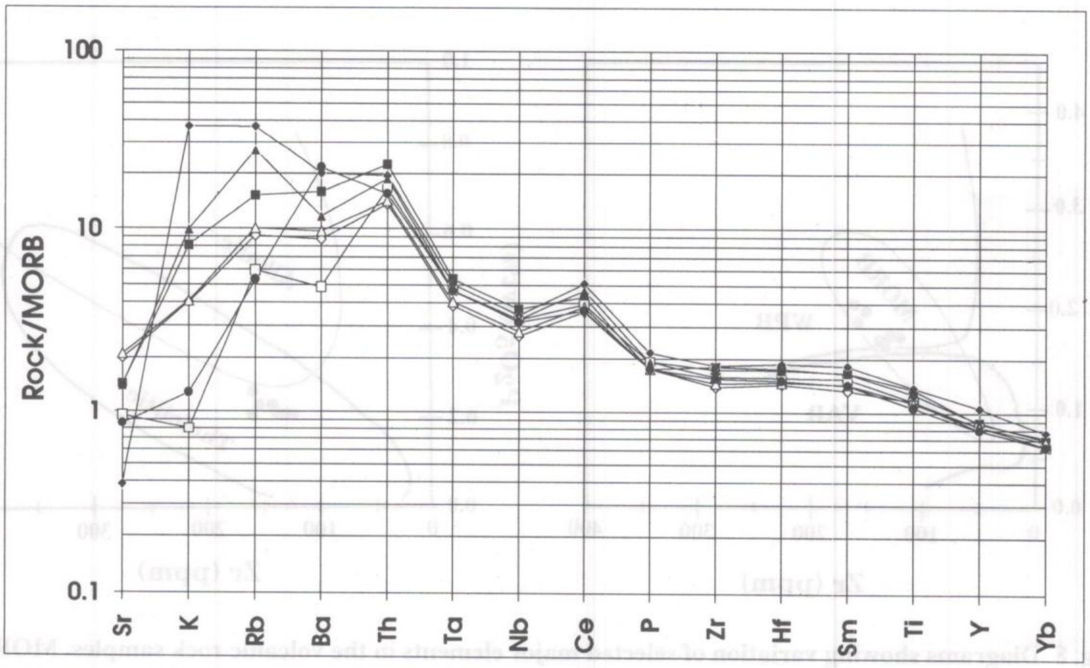

Fig. 9(b) MORB-normalized trace element variation diagram (Pearce 1983) for Dowar Khola volcanic rock samples. Legend as in Fig. 9(a)

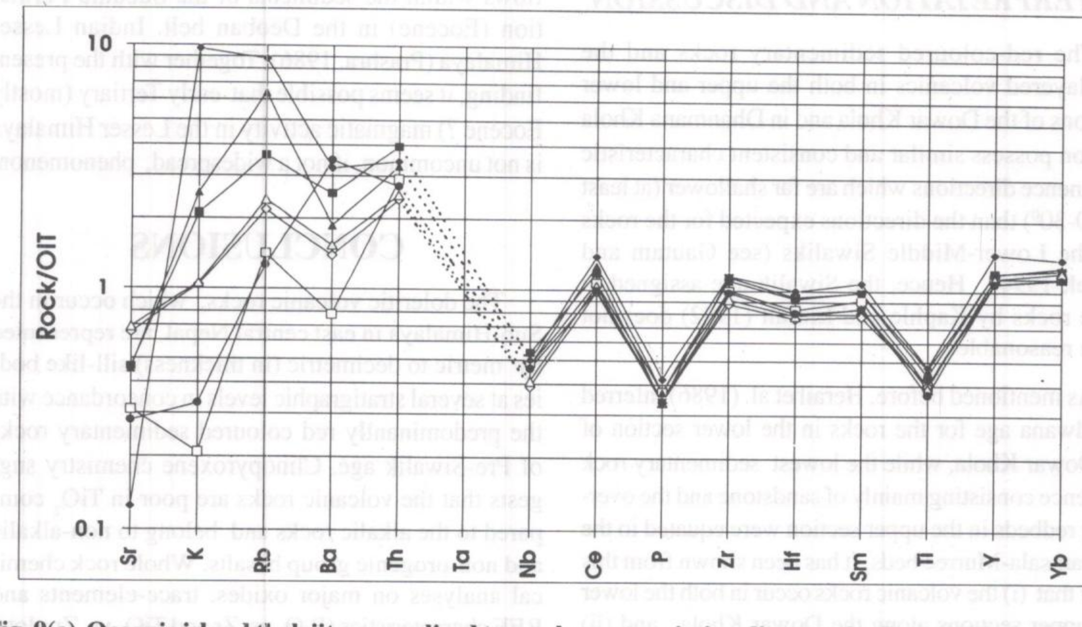

Fig. 9(c) Oceanic island tholeiite normalized trace element variation diagram for Dowar Khola volcanic rock samples. Dashed lines connect data points where intermediate points are missing. Normalisation factors after Wilson (1993). Legend as in Fig. 9 (a)

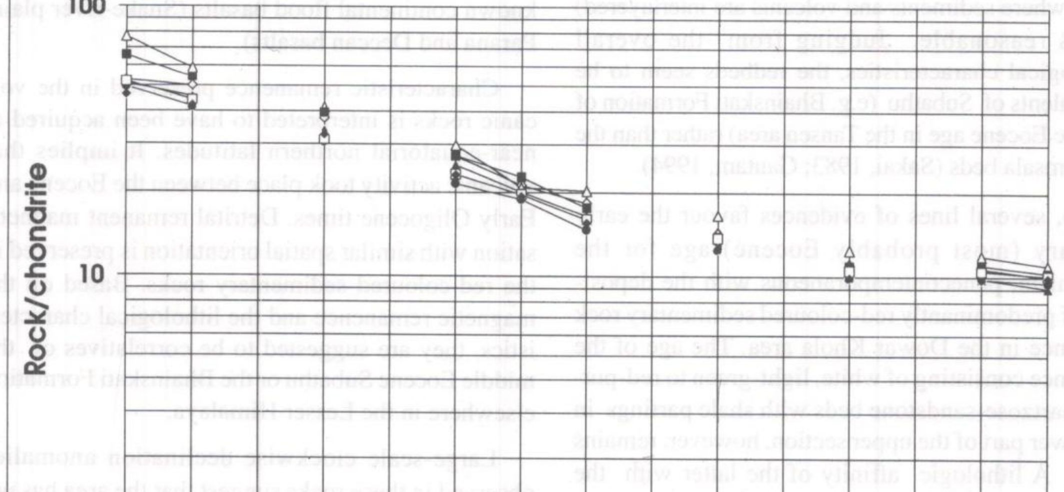

Fig. 10 Chondrite-normalized rare earth element patterns for Dowar Khola volcanic rock samples. Normalisation constants from Nakamura (1974). Legend as in Fig. 9(a)

INTERPRETATION AND DISCUSSION

The red-coloured sedimentary rocks and the interlayered volcanics in both the upper and lower sections of the Dowar Khola and in Dhanmana Khola section possess similar and consistent characteristic remanence directions which are far shallower (at least by 20-30^0) than the directions expected for the rocks of the Lower-Middle Siwaliks (see Gautam and Appel, 1994). Hence, the Siwalik age assigned to these rocks by Kaphle and Einfalt (1992) does not seem reasonable.

As mentioned before, Herail et al. (1986) inferred Gondwana age for the rocks in the lower section of the Dowar Khola, while the lowest sedimentary rock sequence consisting mainly of sandstone and the overlying redbeds in the upper section were equated to the Dharamsala-Murree beds. It has been shown from this study that (i) the volcanic rocks occur in both the lower and upper sections along the Dowar Khola , and (ii) the red sediments and the volcanics in both the upper and lower sections and also those in the Dhanmana section possess similar natural remanence. So, the same age range for the rocks in both sections (at least those parts, where sediments and volcanis are interlayered) seems reasonable. Judging from the overall lithological characteristics, the redbeds seem to be equivalents of Subathu (e.g. Bhainskati Formation of Middle Eocene age in the Tansen area) rather than the Dharamsala beds (Sakai, 1983; Gautam, 1994).

So, several lines of evidences favour the early Tertiary (most probably Eocene) age for the volcanism, penecontemporaneous with the deposition of predominantly red-coloured sedimentary rock sequence in the Dowar Khola area. The age of the sequence consisting of white, light-green to red-purple quartzose-sandstone beds with shale partings in the lower part of the upper section, however, remains open. A lithologic affinity of the latter with the rock sequence of Amile Formation (mainly Paleocene-Eocene) of the Tansen Group is inferred (Sakai 1983; Gautam 1994).

The timing of the volcanic activity suggested here is in accordance with the Eocene volcanism evidenced by the occurrence of basic rocks comprising basalt and diabase as penecontemporaneous lava flows within the sediments of the Subathu Formation (Eocene) in the Deoban belt, Indian Lesser Himalaya (Prashra, 1986). Together with the present finding, it seems possible that early Tertiary (mostly Eocene ?) magmatic activity in the Lesser Himalaya is not uncommon, if not a widespread, phenomenon.

CONCLUSIONS

The doleritic volcanic rocks, which occur in the Sub-Himalaya in east central Nepal, are represented by metric to decimetric (in thickness) sill-like bodies at several stratigraphic levels in concordance with the predominantly red coloured sedimentary rocks of Pre-Siwalik age. Clinopyroxene chemistry suggests that the volcanic rocks are poor in TiO_2 compared to the alkalic rocks and belong to non-alkalic and non-orogenic group basalts. Whole rock chemical analyses on major oxides, trace-elements and REE characteristics (P_2O_5 vs. Zr and TiO_2 vs. Zr plots; rock/OIT, rock/MORB, rock/chondrite spidergrams) indicate their affinity to the tholeiitic within plate basalts (WPB). Spidergrams, Y/Nb vs. Zr/Nb plots and La/Nb ratios show similarity to the commonly known continental flood basalts (Snake-river plain, Parana and Deccan basalts).

Characteristic remanence preserved in the volcanic rocks is interpreted to have been acquired at near-equatorial northern latitudes. It implies that volcanic activity took place between the Eocene and Early Oligocene times. Detrital remanent magnetisation with similar spatial orientation is preserved in the red-coloured sedimentary rocks. Based on the magnetic remanence and the lithological characteristics, they are suggested to be correlatives of the middle Eocene Subathu or the Bhainskati Formation elsewhere in the Lesser Himalaya.

Large-scale clockwise declination anomalies observed in these rocks suggest that the area has undergone rotation since the acquisition of the primary remanence. As these rocks are bounded by thrusts from the Siwaliks from both (i.e. north and south) sides and are sandwiched in between, most likely they constitute tectonic slice(s), probably slipped up from beneath the Siwaliks in the outer Lesser Himalaya.

The paleomagnetic data obtained so far are of preliminary nature and so the interpretation is tentative. The volcanic rocks and the redbeds as well seem to occur in several other river sections towards the east and west of the present study area, eg. along Sokan Khola, Basan Khola etc. (Adhikary and Rimal1994) and should be the objects of future paleomagnetic study for a better stratigraphic and tectonic interpretation. For volcanic rocks, studies on magnetic fabric and rock-magnetic properties will be very much desirable to see the relationship between the anisotropy of magnetic susceptibility and the magnetic remanence.

ACKNOWLEDGEMENTS

We express our sincere thanks to Patrick Le Fort, C.N.R.S, Grenoble, France for his generous help in arranging the whole rock chemical analyses. Mr. S. N. Sapkota is thankfully acknowledged for the assistance during the field sampling. PG gratefully acknowledges the Royal Nepal Academy of Science and Technology (RONAST), Kathmandu, for providing the research grant for the paleomagnetic research on redbeds.

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