Remote sensing-based hazard assessment of glacial lakes in Sikkim Himalaya

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Glacial lake is a water body formed in/under/besides and/or in front of a glacier due to glacial dynamics. Such high-altitude glacial lakes are hazardous to humanity and infrastructure as they can drain instantaneous and create devastating floods in the downstream. The formation of moraine-dammed glacial lakes and glacial lake outburst flood (GLOF) is major concern in countries such as Bhutan, Tibet (China), India, Nepal and Pakistan. The temporal satellite data analysis from CORONA to LISS III shows the glacier receded 1.9 km from 1962 to 2008 and the formation of a moraine-dammed glacial lake at the snout of South Lhonak glacier, Sikkim Himalaya. The lake outburst probability shows a very high value of 42% for the lake and peak discharge estimated using the empirical formula shows a discharge of 586 m^3/s. A systematic inventory of glacial lakes using high-resolution satellite data and *in situ* field survey is recommended and adaptation measures like early warning systems and mitigation measures are required in potential GLOF areas.

Keywords: Glacial lakes, hazard assessment, outburst floods, remote sensing.

GLOBAL climate change during the twentieth century had a significant impact on glaciers and glacial environments. These glacial fluctuations cause the formation and enlargement of glacial lakes in many mountain ranges[1–4]. A glacial lake is defined as a water mass existing in sufficient amount and extending with a free surface in, under, besides, and/or in front of a glacier and originated by glacier activities[5]. Due to increase in the rate of melting of the glaciers, the lakes are increasing in areal extent and water storage capacity. Sudden discharge of large volumes of water and debris from these lakes is termed as glacial lake outburst flood (GLOF). GLOF can cause extensive damage to the natural environment and human property as it can drain extremely rapidly and cause dramatic floods downstream. GLOF can be considered as a geomorphological risk because it is a natural risk which is connected to a geomorphological hazard.

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The GLOF event in Nepal during 1981 damaged the Friendship Bridge of the China–Nepal Highway, destroyed the Koshi power station in Nepal and caused serious economic losses[6]. During August 2000, in the Tibetan Plateau, the GLOF occurred and destroyed more than 10,000 houses and 98 bridges, and financial losses were about 75 million US dollars[7]. In 2008, GLOF from Gulkin glacier, Karakoram Himalayas also damaged several properties[8]. The GLOFs at Dig Tsho in 1985 (Nepal) and Luggye Tso in 1994 (Bhutan) are considered 'textbook' case studies of such events globally.

Recent expansion of glacial lakes in the Himalaya has been mainly studied in North Bhutan[9,10] and in the Everest region[11–15]. The inventory of glacial lakes in Sikkim Himalaya using temporal satellite data shows the occurrence of 320 glacial lakes[1]. The glacial lake hazard vulnerability studied in Shako Cho lake in Sikkim Himalaya shows a high risk of potential for a GLOF[16]. Fujita *et al.*[17] and Bolch *et al.*[15] studied the recent changes in the Imja glacial lake, Mt Everest region of Nepal from multitemporal and multi-sensor satellite data. The glacial lake inventory in SE Tibet using ALOS AVNIR-2 data showed an increase in the number of glacial lakes from 96 to 123 during the period 1970 to 2009 (ref. 18).

In the snow and glaciated terrain of the Himalaya, satellite remote sensing has proven to be the best tool because many of the glacial lakes are located at very high altitude, cold weather and rugged terrain conditions, making it a tedious, hazardous and time-consuming task to monitor by conventional field methods. Satellite remote sensing technology facilitates to study the behaviour of glacial lakes of the Himalaya systematically with a cost-to-time benefit ratio. The remote sensing technology fails, if the glacial lakes are covered under snow/ice and permanently covered under mountain shadows.

In the Indian Himalayan region the first GLOF event was reported when the 1926 flood released by the Shyok glacier, Jammu and Kashmir, destroyed Abudan village and the surrounding land which were at a distance of 400 km from the outburst source[19]. Another report by Sangewar *et al.*[20] depicted sudden emptying of some of the moraine-dammed lakes of Shaune Garang glacier, Himachal Pradesh in 1981 and 1988 based on high discharge measured downstream. In the Indian Himalayan region GLOF studies are limited and not well understood. The present communication reports hazard assessment of South Lhonak lake in Sikkim Himalaya through satellite-based study (Figure 1).

CORONA, Landsat MSS, TM and Resourcesat-1 (IRS P6) LISS III satellite data were used in this study. Apart from satellite data, ASTER digital elevation data (DEM) were also used. Table 1 shows the details of the data used in the present study.

For this study declassified CORONA data of 1962 was used as the base data. In the context of remote sensing, CORONA was the first space reconnaissance programme

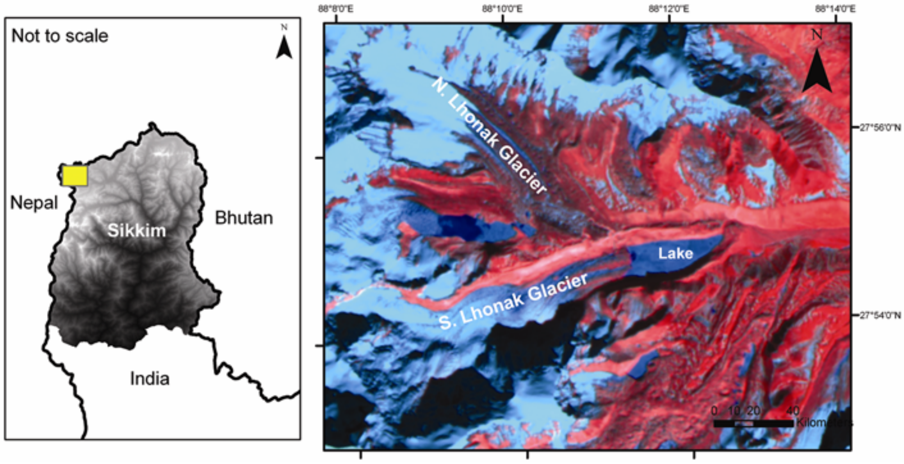

Figure 1. Location map of the study area showing the South Lhonak glacier and the glacial lake.

Table 1. Data used in the present study

Satellite/sensor	Date of acquisition	Spatial resolution (m)
Corona KHA	24 November 1962	4.0
Landsat 2 MSS	23 January 1977	57
Landsat 5 TM	10 November 1989	30
Resourcesat-1	09 November 2002	23.5
LISS III	17 November 2008	
ASTER	DEM	30.0 (vertical)

by the Central Intelligence Agency (CIA) and the US Air Force (USAF), which took data from 1960 to 1972. Using 144 satellite missions (102 were successful), it captured information of the Earth's surface in panchromatic films having mono and stereo capabilities with resolution 1.8, 2.7 and 7.5 m (ref. 21). Declassification of these photographs in 1995 revolutionized the remote sensing community. The lake is present in the CORONA data of 24 November 1962 (Figures 2 and 3) as a supraglacial lake at the snout of the glacier. The first occurrence of a separate lake is marked in the Landsat MSS data of 1977 (Figure 2) and the lake areal extent mapped from the MSS data and retreat of the glacier were also measured. In 1977, the lake had an areal extent of 17.54 ha and was attached to the glacier terminus. The lake areal extent was also mapped from temporal satellite data of 1989, 2002 and 2008 (Figure 4). The lake area increased by an extent of 81.1 ha from 1977 to 2008.

The glacier boundary was also mapped from Landsat TM (1989) and Resourcesat-1 LISS III (2002 and 2008) data. Glacier boundary was delineated from satellite data using standard FCC combination of bands and image enhancement techniques applied to differentiate glacial and non-glacial features. The glacier retreat measurements were carried out along the centre line of the glacier. The change detection study revealed that the glacier retreated 1.9 km during the 46-year period of 1962–2008. Figure 4 and Table 2 show the extent of glacial lake in

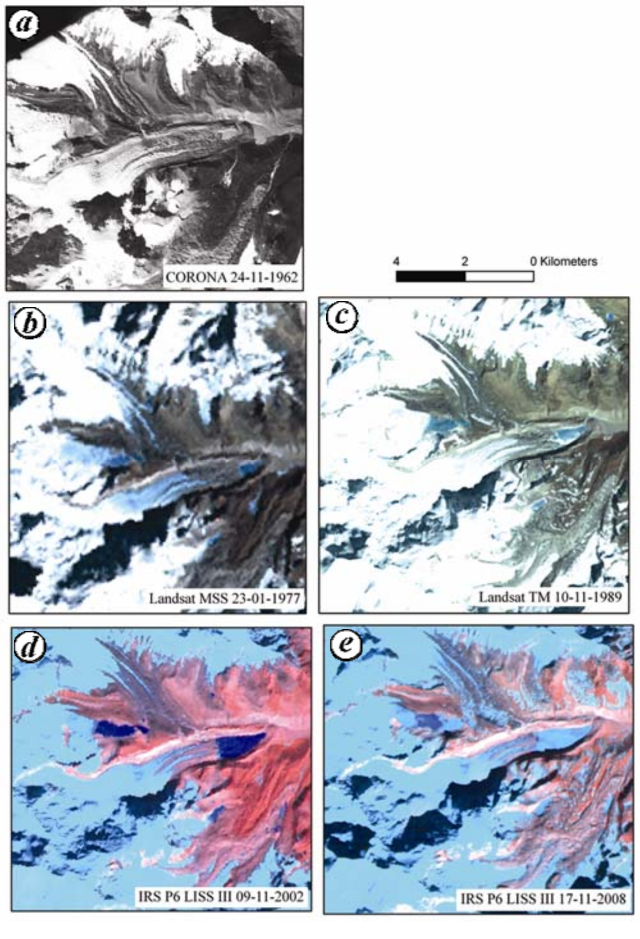

Figure 2. Maps showing the glacial lake in different time-periods. ***a***, 1962 CORONA data of the glacier. ***b–e***, Growth of the glacial lake in 1977, 1989, 2002 and 2008 respectively.

different time-periods and retreat of the glacier. The 2008 satellite imagery shows that the lake is still attached to the snout, but is expanding laterally and increasing in areal extent and bounded by moraines and hence characterized as moraine-dammed lake (Figure 5).

The depth measurements of the lake were carried out using ASTER DEM. Lake depth measurements were derived from the contour map generated from ASTER DEM. The bounding moraine height of the lake and central part of the lake are considered for calculating the depth of the lake (Figure 5). For further analysis the depth of the lake is taken as ~20 m. The areal extent of the lake was measured as 98.7 ha in 2008. The volume of the lake is estimated as the product of area and depth and calculated possible lake volume is 19.7 million m^3.

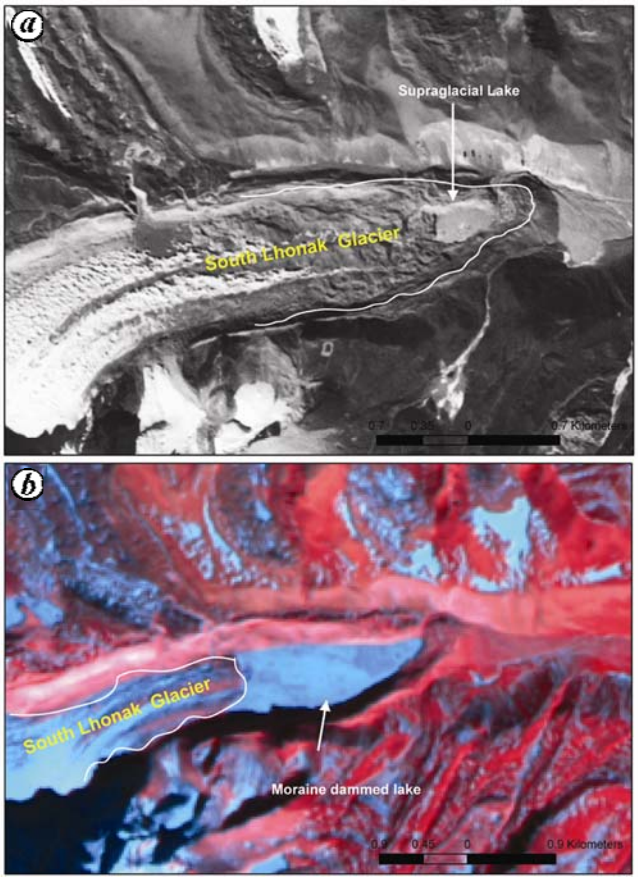

Figure 3. Satellite images showing the glacial lake in 1962 and 2008. ***a***, CORONA data of 1962 showing the glacial lake as a supraglacial lake at the snout. ***b***, 2008 LISS III data showing the glacial lake as a moraine-dammed lake.

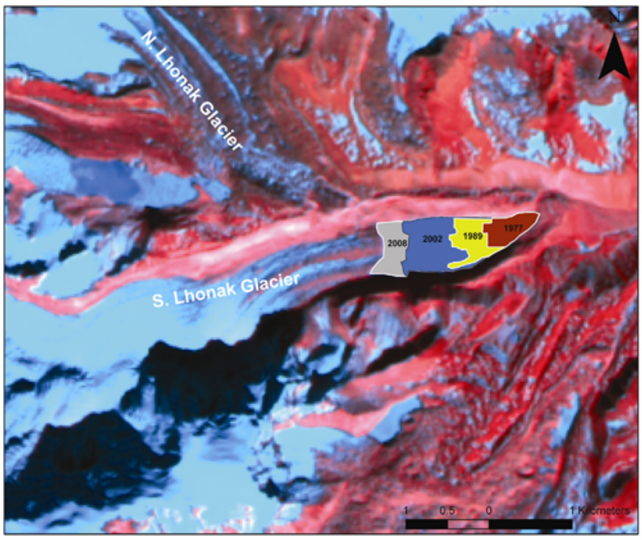

Figure 4. Satellite data of 2008 showing the growth of the lake in different time-periods and retreat of the glacier.

The extent of a flood caused by the breach of a moraine dam is relevant for further hazard analyses. The present study used the outburst probability model developed by McKillop and Clague[22] for assessing the dangerous nature of the moraine-dammed lake and the equation proposed by Costa and Schuster[23] for estimating the peak discharge of the lake in case of an outburst.

McKillop and Clague[22] developed the moraine-dammed lake outburst probability model by considering the utility of remote sensing in gathering information and also based on the inventory of 175 moraine-dammed lakes in British Columbia.

$$P = \{1 + \exp - [\alpha + \beta_1(\text{M\_hw}) + \sum \beta_j(\text{Ice\_core}_j) + \beta_2(\text{Lk\_area}) + \sum \beta_k(\text{Geology}_k)]\}^{-1},$$

where α is the intercept, β_1, β_j, β_2 and β_k are the regression coefficients for M_hw (moraine height-to-width ratio), Ice_core (moraine – ice free or ice core), Lk_area (lake area) and Geology (moraine constituents – sedimentary, metamorphic) respectively.

The parameters such as moraine height-to-width ratio can be derived using digital elevation data by overlaying the satellite data over the DEM. Presence/absence of an ice-core in the moraine is established using the following methods proposed by McKillop and Clague[22]; (i) a moraine with a rounded surface with minor superimposed ridges was assumed to be ice-cored; (ii) a moraine with a disproportionately large end in front of a small glacier

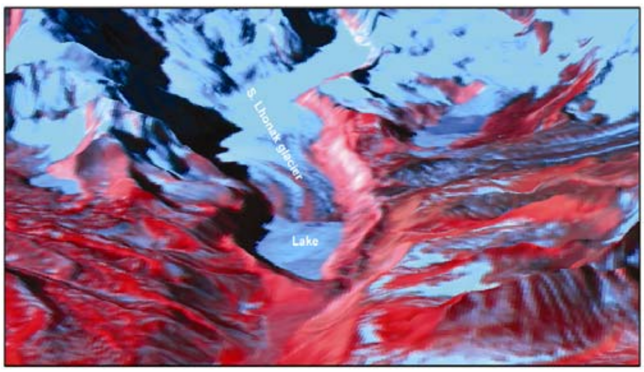

Figure 5. Three-dimensional perspective view of the glacier and the moraine-dammed lake.

Table 2. Area of the lake and retreat of the South Lhonak glacier estimated from temporal satellite data

Time-period	Area of the lake (ha)	Different time-periods	Retreat of the glacier (m)
1977	17.54	1962–1977	675.3
1989	37.32	1977–1989	443.8
2002	78.95	1989–2002	511.4
2008	98.73	2002–2008	310.5
Total retreat		1962–2008	1941

Table 3. Parameters used for estimation of outburst probability model

Variable	Category	Coefficient	Estimated value
Intercept	–	–7.1074 (α)	–
M_hw	–	9.4581 (β_1)	0.031
Ice_core_j	Ice-free	1.2321 (β_j)	–
Lk_area		0.0159 (β_2)	98.73 ha
$Geology_k$	Metamorphic	–8.4968 (β_k)	–

was suspected to be ice-cored and (iii) a narrow, sharp-crested moraine with an angular cross-section was interpreted to be ice-free. The lake area is estimated from the lake boundary layer prepared from satellite data and main rock type forming the moraines is derived from the lithological interpretation of the study area.

The regression parameters taken from McKillop and Clague[22] and the four predictors taken from satellite data of 2008 are given in Table 3. The M_hw value taken from satellite data was used to measure moraine height and width of the lake. For further analysis, the height of the moraine is taken as ~ 20 m and average width is ~ 630 m. The areal extent of the lake was measured as 98.73 ha in 2008 from satellite data.

After the assessment of hazard probability, maximum flood discharge from the moraine dam failure was estimated using the empirical model developed by Costa and Schuster[23].

$$Q_p = 0.00013(\mathrm{PE})^{0.60},$$

where Q_p is the peak discharge (m^3/s) and PE the potential energy of the lake water which is the product of dam height (m), lake volume (m^3) and the specific weight of water (9800 N/m^3). This model was developed based on eight moraine-dammed lake outburst events and the results are reliable for peak discharge[24].

Moraine-dammed lake volume was estimated by the following relation developed by O'Connor *et al.*[24].

$$V = 3.114A + 0.0001685A^2,$$

where V is the lake volume (m^3) and A the area of the lake (m^2).

However, because of non-accessibility of features such as ice thickness, lake temperature, length of drainage tunnel, bathymetry of the lake, etc., it is difficult to apply other models for this study, which may give rise to inaccurate results. Therefore, the model is used for early assessment of lake hazard probability and peak discharge only.

From 1962 to 1977, the glacier retreated 675 m and created a separate lake having area of 17.54 ha. Temporal satellite data of 1989, 2002 and 2008 show that the glacier retreated 1.9 km from 1962 and consequently the lake is increasing in areal extent. Progressive enlargement of supraglacial lakes in the Himalaya is a well-researched topic[9,13,25]. Imja glacial lake in Nepal increased from a few small ponds in the 1950s to a single body of water[26] with a surface area greater than 0.5 sq. km in 1984. Various studies suggest that supraglacial lakes accelerate the disintegration of glacier ice by draining water through the cracks in the ice as well as melting at the glacier bottom[27,28]. Figure 6 shows a simple model depicting the formation of moraine-dammed glacial lake from a supraglacial lake and subsequent retreat of the glacier.

The temporal satellite data analysis from 1962 to 2008 (Figures 3 and 4) indicates the present moraine-dammed glacial lake formed initially as a supraglacial lake and subsequent recession of the glacier caused its enlargement. The growing nature of the lake can cause dangerous GLOFs. An ICIMOD report[29] shows that the South Lhonak glacial lake already had an outburst event evidenced from breach of the moraine dam. This clearly indicates the hazardous nature of the glacial lake.

By considering the probability model of McKillop and Clague[22] and incorporating the predictor parameters, the model yields a very high outburst probability of 42% (<6% very low; 6–12% low; 12–18% medium; 18–24% high; > 24% very high). The very high outburst probability shows that, if the lake increases its extent in due course of time, it may cause a dangerous outburst flood. This is a preliminary assessment of a probability only and more field-based studies are needed for proving the hazardous potential.

As mentioned earlier, the lake volume is 19.7 million m^3 and lake depth is 20 m; peak discharge is estimated using the formula developed by Costa and Schuster[23]. Considering the average summer discharge of Chhota Shigri nala in Himachal Pradesh 10 m^3/sec (ref. 30) the resultant discharge from the moraine-dammed lake is high and its value is 586 m^3/sec using the above-mentioned

formula[23]. Due to the lack of field data the modelled discharge error is unknown. According to the discharge data the lake seems to be hazardous. However, such kind of natural hazards are non-predictable and may have trans-boundary impacts as well. In the Indian Himalayan region, flash floods from sudden downpour due to cloud-burst are common in the monsoon season. Forming cloudburst over the moraine-dammed glacial lake can cause dangerous GLOFs.

Lake area and volume are of primary importance because they define the amount of water available for an outburst. This study indicates that the moraine-dammed lake was formed from the supraglacial lake after 1962 and its dimensions are continually changing due to the glacier retreat. The rate of growth of the lake indicates possible developments of the hazard situation. Change detection techniques based on satellite image time series are especially useful in such cases. The methods proposed here are intended to enable rapid hazard assessments over large areas of glacier lakes in remote, inaccessible, high-mountain regions.

This communication presents the utility of remote sensing in detecting and monitoring the hazardous nature of glacial lakes in highly glaciated terrain of the Indian Himalaya. Empirical models allow an approximate estimate of a potential GLOF hazard. If the preliminary study indicates a severe hazard potential, more detailed field surveys may be required to establish the risk of GLOF. In view of fast retreating glaciers in the Himalaya, to establish the hazard potential of glacial lakes a systematic inventory of these lakes using high-resolution satellite data and *in situ* field survey is recommended and adaptation measures like early warning systems and mitigation measures are required in potential GLOF areas. The study recommends the potential use of the high-altitude glacial lakes as a storage mechanism for the controlled utilization of the melt water.

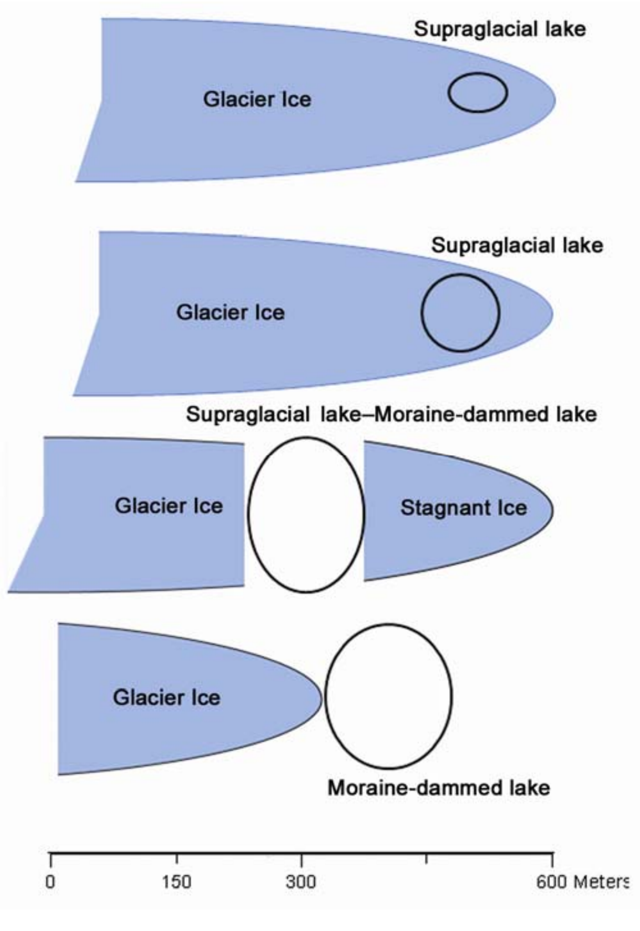

Figure 6. A simplified model showing the formation of a moraine-dammed lake from a supraglacial lake and recession of a glacier.

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Palaeomagnetism of Khairmalia Volcanics, south of Chittorgarh – implications related to the basal age of the Proterozoic Vindhyan Supergroup

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Palaeomagnetic studies were carried out on the basal Khairmalia volcanic rocks of the Proterozoic Vindhyan Supergroup. Two hundred and ten specimens prepared from 30 oriented block samples from 10 sites near Khairmalia, south of Chittorgarh, Rajasthan were studied. They are characterized by mean characteristic remanent magnetization $D = 8°$ and $I = 9°$ ($\alpha_{95} = 16.3$; $k = 23.11$). Virtual geomagnetic pole is estimated at 68.6°N; 231.3°E ($dp = 8.3$ and $dm = 16.4$). Plot on the Proterozoic apparent polar wander path[1] indicates that the volcanics may have erupted ca. 1800 Ma.

Keywords: Chittorgarh, Khairmalia andesites, palaeomagnetism, Vindhyan Supergroup.

THE Vindhyan Supergroup consists of about 4200 m thick sedimentary and volcanic rock sequence. In the western part, the rocks of the Vindhyan Supergroup largely occur in Chittorgarh, Bhilwara, Bundi, Kota and Sawai Madhopur districts of southeastern Rajasthan. Lava flows and volcaniclastic rocks known as Khairmalia volcanic rocks occur south of Chittorgarh. They constitute the basal formation of the Vindhyan Supergroup in southeast Rajasthan. In this communication we report the results of palaeomagnetic studies of these rocks. This work has been taken up to find out the apparent polar wander path (APWP) for the Indian subcontinent during the late Palaeoproterozoic, which is an important period when sedimentation of the Vindhyan Basin began. Recent studies[1–3] show that the age of the lower Vindhyan supergroup is as old as 1601 m.y. We examine the results of palaeomagnetic studies of the volcanics whose age is known through geochemical studies[4].

Khairmalia volcanic rocks occur in a 50 km long linear belt south of Chittorgarh. They are well exposed near Khairmalia, Katai-Madhopur, Madhur Talab and along Jakham river near Kharveri. Figure 1 shows the geological map of the area. Good outcrops are seen between Until and Khairmalia east of Katai-Madhopur, east of Dholapani,

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