Open access e-Journal
**Earth Science India,** eISSN: 0974 – 8350
Vol. 4(I), January, 2011, pp.1-14
http://www.earthscienceindia.info/

# Record of Neotectonic Activity in the Pindari Glacier valley: Study based on Glacio-geomorphic and AMS Fabric evidences

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## Abstract

Systematic geomorphological studies aided by anisotropy of magnetic susceptibility (AMS) along the Pindari glacier valley suggest continued neotectonic activity in the area. The distribution and orientation of a number of glaciogeomorphic features viz. inclined bedding planes within the lacustrine deposits, asymmetrical terraces, deep entrenched gorges, skewed fans, sharp contact between the U-shaped and the V-shaped valleys and higher bifurcation ratio, The shape parameters $T$ and $q$ determined during the systematic AMS study of a glacio-lacustrine pit profile suggests that during its depositional history, there have been at least two phases, where the primary sedimentary fabric has been overprinted by secondary tectonic fabric. The constricted valley indicates a major phase of rejuvenation prior to 25 ka that inhibited the downstream advancement of Pindari trunk glacier. This was followed by another event of rejuvenation post 3 ka.

**Key words:** Neotectonics, Pindari glacier, Anisotropy of magnetic susceptibility, Geomorphology, Kumaun Himalaya.

## Introduction

The Pindari glacier lying between the latitude 30º 06' 30" N to 30º 19' 00" N and longitude 79º 55' 30" E to 80º 05' 30" E, is relatively a smaller glacier of Alaknanda basin falling in the Bageshwar district, Uttarakhand (Fig.1). The Pindar River emanating out of the glacier is an important tributary of Alaknanda River and meets it at Karnprayag. In the upper reaches, Pindar River flows along a faulted valley. Geologically, the study area consists of the rocks of Pindari Formation of Vaikarta Group (Valdiya, 1999). The Pindari Formation constituted of gneisses and schists with lenses of calc-silicate rocks is bounded by Trans-Himadri Fault on the northern side and Pindari Thrust on the southern side. It is intensely injected by Tertiary pegmatites and granites (Badrinath Granite) leading to the development of migmatites, and the Budhi Schist comprising of biotite-rich calc-schists (Valdiya, 1973; Valdiya and Goel, 1983).

The Himalayan belt in general shows abundant evidences of crustal adjustments (Khattri *et al.,* 1994; Acharya, 1982; Gaur, 1994). The neotectonics throughout the Himalaya is attributed to the continuous northward push of the Indian plate (Molnar, 1986; Valdiya, 1993). The studies carried out earlier in the Gangotri glacial valley (Bali *et al.,* 2003) suggest that neotectonics plays an important role in the glacio-geomorphic evolution of the glaciated terrains. The proxy records of past glaciation along the valley are preserved in the form of various erosional and depositional landforms. A number of these landforms have been modified by subsequent denudational processes.

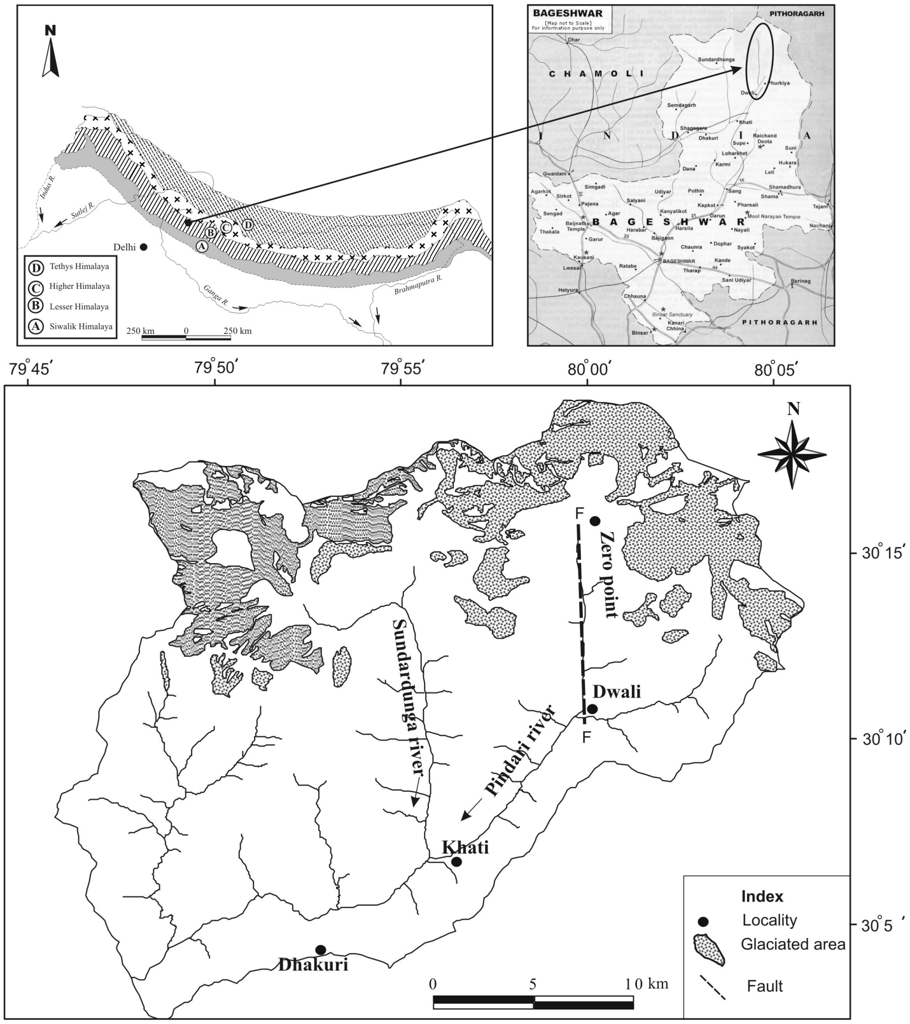


**Fig. 1:** Location map of the study area.

The analysis of the anisotropy of magnetic susceptibility (AMS) is a useful tool to understand sedimentary and tectonic character of a weakly deformed sedimentary unit (Sinha *et al.,* 2009). It has been applied to rock fabric investigation. The AMS study has become an important tool for studying tectonic events, global climate and environmental changes, in past few decades (Sangode *et al.,* 2001). The most successful application of AMS analysis is in the study of ductile deformation of rocks. Earlier workers have shown that magnetic fabric provides a reliable indicator of strain (Graham, 1966; Henry, 1973; Hrouda, 1979; Hrouda and Janak, 1976; Hrouda *et al.,* 1978; Kligfield *et al.,* 1977, 1982). Several studies on AMS in weakly deformed sediments from various environments have been carried out (Agarwal *et al.,* 2002.). These studies have shown that systematic analysis of magnetic fabrics can lead to tectonic inferences (Hounslow, 1990; Owens, 1993; Housen *et al.,* 1993; Agarwal *et al.,* 2002; Jelinek, 1981; Tarling and Hrouda, 1993). This method has proved to be a useful tool in structural analysis of weakly deformed sediments in various environments. As per the knowledge of authors, AMS studies have so far not been used for inferring the neotectonic activity in the glaciogenic sediments.

In the present study, an attempt has been made to critically observe the imprints of active tectonics in evolution and orientation of different geomorphic units in time and space. Analyzing the orientation of magnetic fabric has further helped in assessing the role of active tectonics in the morphotectonic evolution of the area.

## Evidence of Active Tectonics

Due to the continuous northward movement of the Indian plate, the Himalayan mountain belt is still under the process of crustal adjustments. These adjustments are translated in the form of neotectonic activity experienced in different segments of the Himalaya and in turn are manifested in the form of distinct landforms (Valdiya, 1993). Surface processes in the Himalaya have also been found to be controlled by climatic changes. Major landscape development has been recorded during the glacial and non-glacial climatic changes (Bernard *et al.,* 2006; Dortch *et al.,* 2008). The proxy records of Late Quaternary glacial activity in the Pindar valley are well preserved in the form of glacially sculptured landforms. The evolution and the present day disposition of these landforms seem to be influenced by the neotectonic activity. The control of active tectonics on the evolution of glacial and periglacial landforms in the Gangotri glacier valley have been documented earlier (Bali *et al.,* 2003).

The geomorphic features of the area include the U-shaped glacial troughs of the trunk and the tributary glaciers, lateral morainic ridges of different time periods, recessional moraines, hanging valleys, debris fans at the base of tributary glaciers, outwash plains, kame terraces, earth pyramids etc.

## Impact of Active Tectonics on Evolution of Glacial Landforms

### Modified U- shaped valleys:

The upper reaches of Pindar valley extending from the snout up to 7 km downstream shows a typical U-shaped valley. The chronology of glaciation based on moraine stratigraphy established using the OSL dating suggests that there have been at least four major episodes of glacial advancements that have taken place at around 60-55 ka, 25 ka, 3ka and lastly during the Little ice age (Bali *et al.,* 2010). The earlier U-shaped valley has been incised and modified into a V-shaped valley around 1.3 km upstream of Phurkia (Fig. 2). Such an activity seems to have been initiated in response to major episode of active tectonics prior to 25 ka. The valley constriction thus caused due to the then tectonic activity, seems to have restricted further downstream advancement of Pindari trunk glacier during the second phase. Sharp contact between the U-shaped with the V-shaped valleys as well as the modification of the U-shaped valley along its floor has been documented to have been initiated due to the reactivation of earlier fractures under the existing active tectonic regime with similar conditions in the Gangotri region also (Bali *et al.,* 2003).

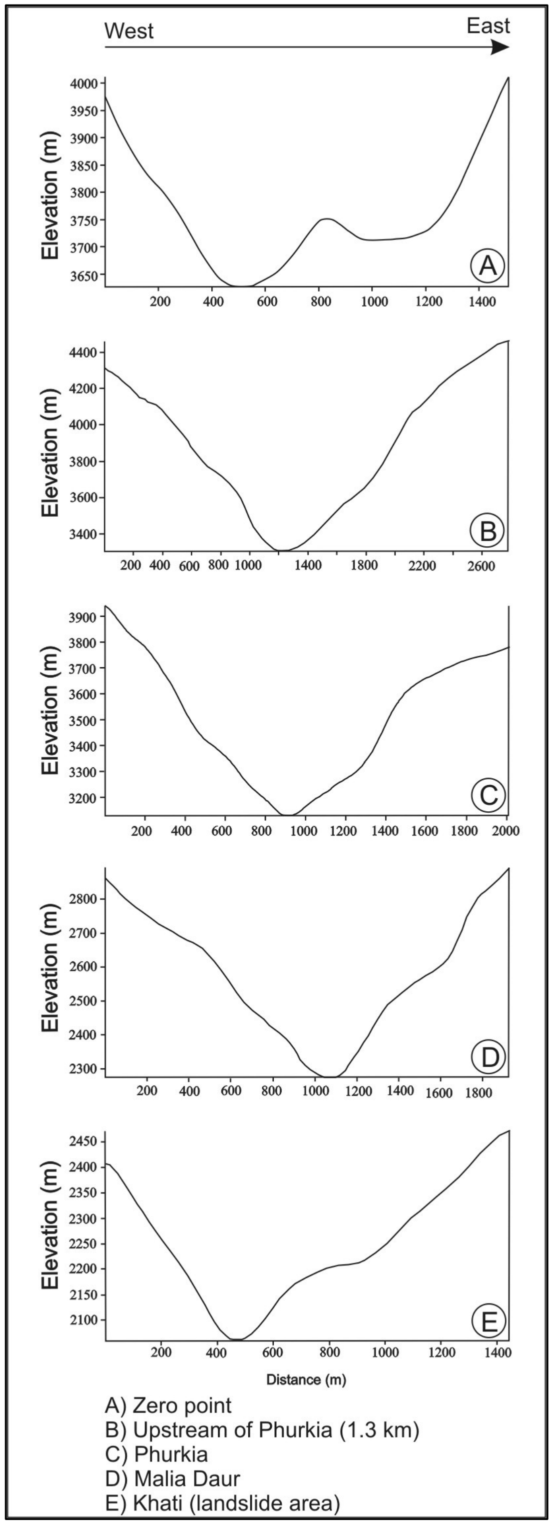


**Fig. 2:** Valley profiles made across the Pindari valley from snout of Pindari glacier up to Khati village.

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**Inclined glacio-lacustrine beds:**

Downstream of the Pindari Glacier snout, a glacio-lacustrine deposit constituted of silty to sandy material is found well preserved at the summit of the left lateral moraine, formed during the third phase of glacial recession. This N-S striking deposit is located almost at an altitude of 150 m above the valley floor and shows an inclination of about $25^0$ towards east direction (Fig. 3a). OSL dating of this deposit indicates it to have formed around 3 ka (Bali *et al.,* 2010). Such disposition is attributed to a phase of active tectonics that took place post 3 ka.

**Asymmetrical fluvial terraces and River entrenchment:**

The Pindar River flowing along a broad U-shaped valley in the upper reaches follows an N-S oriented fault, referred here as the Phurkia Fault. Recent movements along this fault seem to have been responsible for the geomorphic disposition of the area, especially in the upper reaches. At number of places, the earlier broad U-shaped valley (formed during the past glacial episodes) is seen to have been incised, as a result of which deep gorges are encountered (Fig 3b). During the process of incision, the Pindar River has cut through the earlier glacio-fluvial deposits as well as the valley walls (constituted of crystalline rocks). At some places like Malia Doar and down stream of Phurkia, deep gorges are observed. At around 500 m upstream of Phurkia, a large fan emanating out of the left valley wall is found to be vertically incised. Its spread seems to be checked by the Phurkia Fault.

The movement along the Phurkia fault has further led to the formation of asymmetrical terraces near Phurkia as well as Amula village (Fig. 3c). The river flows through a deep gorge and shows a higher degree of vertical incision in response to the upliftment of the area.

**Skewed fans:**

The recession of Pindari trunk glacier especially during the later phase led to the retreat and extinction of a number of tributary glaciers. As a result, a number of debris cones/ fans coming out of the hanging valleys have modified the geomorphology of the upper reaches (upto around Phurkia) to a great extent. Fan building activity is seen to be more pronounced along the left valley wall where medium to large fans have been incised by the Pindar River. Some of these fans, especially the one located upstream of Phurkia and the other adjacent to the Jeha Gair (near camping ground) have attained a large dimension. These large fans are found to have overprinted the preexisting left lateral moraines (formed earlier by the receding tributary glaciers) along the left valley wall. Most of these fans are disposed normally (at right angles) to the valley wall. However, two fans located at the proximity of Kupi Daur, near the snout are skewed (Fig. 3e). The skewness of these fans has resulted due to the recent tectonic activity (post- Little ice age time). Moreover, the entire extent of the large fan located upstream of Phurkia shows a thick cover of organic material rich soil and a very luxurious alpine type vegetation (meadows), which is not observed in the other upstream fans. It is thus inferred that this fan has been existing since a much longer time as compared to the fans in the upstream region. Long time exposure has facilitated the pedogenic processes to operate over this particular as well as the fans situated downstream. It is very likely that the advancement of the Pindari glacier up to a few hundred meters upstream of this fan at around 25 ka has modified the geomorphology upstream. The downstream part of the valley (to which this fan belongs) escaped the denudation/modifications caused due to glacial advancement and thus facilitated the pedogenic process to operate.

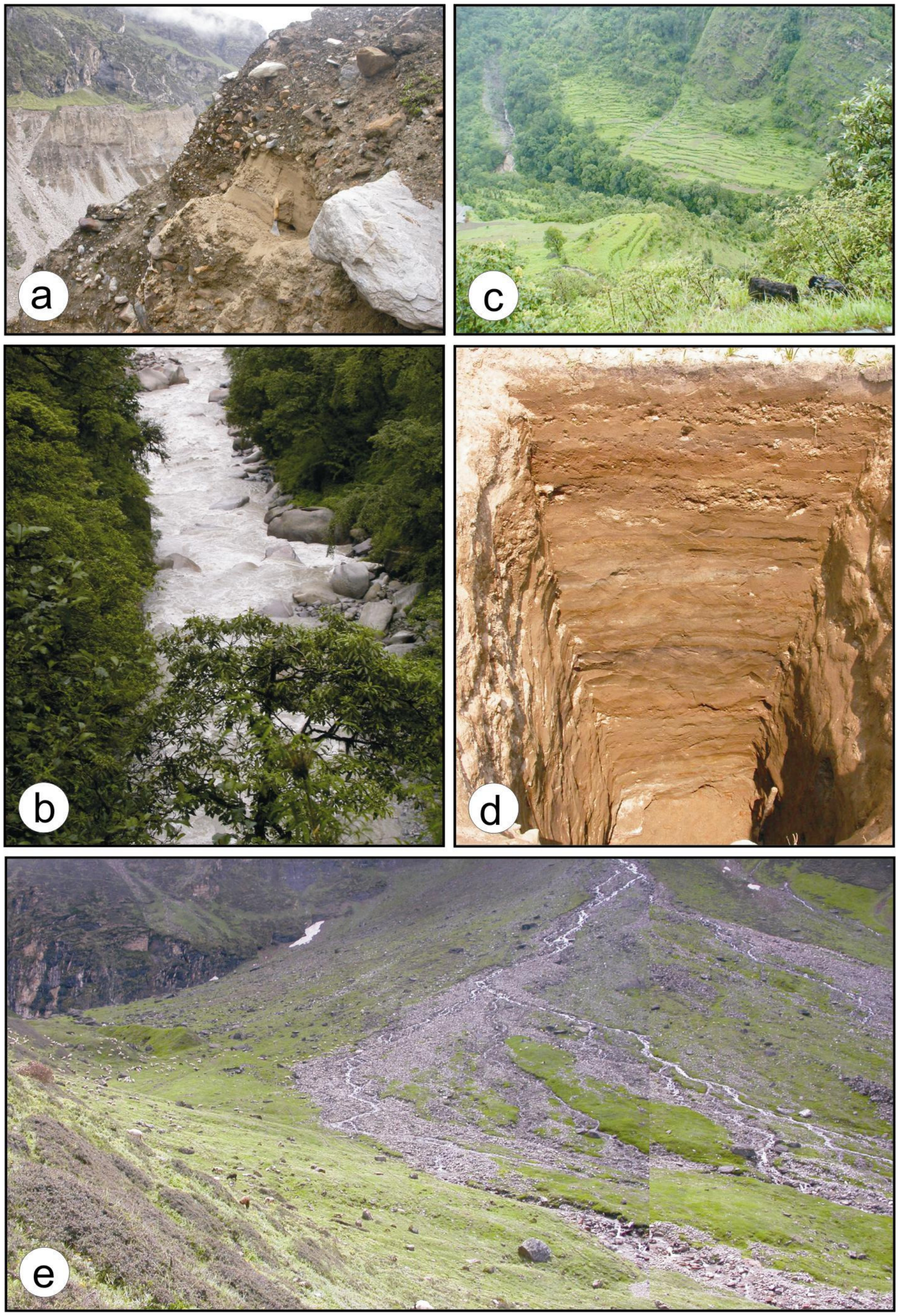


**Fig. 3:** a) Inclined sedimentary beds within the lacustrine deposits. b) Entrenched river channel near Malia Daur. c) Asymmetrical river terraces present near Amula village. d) Pit profile within the right kame terrace at 2 kms upstream of Pindar River from Phurkia. e) Skewed debris fan at Kupi Daur.

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## Anisotropy of magnetic susceptibility (AMS) Studies

The technique is based on the study of major and minor axes of magnetic mineral grain within the host (sediments) material. The magnetic minerals within the sediments may get oriented either during the deposition and compaction or during subsequent tectonic activity. The AMS is represented as a tensor ellipsoid with three principal axes which are expressed as

$K_{max}$ = maximum susceptibility
$K_{int}$ = intermediate susceptibility
$K_{min}$ = minimum susceptibility

These principal axes provide two types of information i.e. directional information of the source represented by the orientation of magnetic minerals (magnetic lineation- *L*, magnetic foliation- *F,* and shape of ellipsoid- *T*).

During the present study, an attempt has been made to deduce recent tectonic activity in the Pindari glacier valley. The work aims at finding the signals of neotectonic activity by using AMS studies. The study also opens new dimensions to identify zones of intense neotectonic activity in the glaciated terrains possible at different times in the recent past.

A 123 inches deep pit has been excavated in the glacio-lacustrine deposits present with in the kame terrace between the right lateral moraine and the valley wall about 4 km downstream of the present day Pindari glacier snout (Fig. 3d). The pit shows different litho-units. The pebble/gravel horizon is found to be interlayered with relatively thicker sandy and organic material rich sandy horizons. Throughout the vertical extent of the pit, north oriented samples have been collected in 2x2x2 cm cubical non-magnetic sampler. While collecting the oriented AMS samples, the pit profile has been initially scrapped, cut, and gelled. Later on, the gelled part was cut into required dimensional cubes and finally put into the cubical plastic sample holders. The AMS parameters (Jelinek, 1981) such as *L*, *F*, *T*, *q*, the degree of anisotropy of the susceptibility ellipsoid *(P)*, and its corrected measure *(P')* were determined to evaluate the magnetic fabrics in the studied samples (Table-1).

### Orientation of AMS:

The anisotropy of magnetic susceptibility (AMS) was measured in all the cubical samples by using the MFK1-FA Kappabridge anisotropy meter (of AGICO, Czech Republic) at Dr. KSKGR Laboratory at Allahabad, India. The fifteen positions measurement routine in low field Susceptibility Bridge provides an accurate estimate of the magnetic anisotropy, which can be represented by a second order tensor (Jelinek, 1981). The analysis yields orientations and magnitudes of the three principal axes of the magnetic susceptibility ellipsoid viz. $K_{max}$, $K_{int,}$ and $K_{min}$ ($K_{1,}$ $K_2$ and $K_3$). Various parameters calculated are derived out of the combination of these values of three axes (Tarling and Hrouda, 1993). The data thus generated was processed by ANISOFT software supplied by AGICO. The shape of the susceptibility ellipsoid is characterized by the shape parameter *T*. When $T < 0$, the ellipsoid is Prolate in shape while it is Oblate when $T > 0$. The eccentricity of the ellipsoid is measured by $P'$ which is the corrected measure of degree of anisotropy of the susceptibility ellipsoid and is related to its degree of sphericity. The parameter showing the mean susceptibility is

$K$m = $[K1 + K2 + K3]/3$. The other important parameters are: magnetic lineation *L,* magnetic foliation *F* and shape factor *q*. (Jelinek, 1981).

**Magnetic Susceptibility:**

The magnetic susceptibility of the samples was measured using a Bartington MS2 Susceptibility meter in low (0.465 kHz) and high (4.65 kHz) frequencies. Low field magnetic susceptibility (xlf) reflects bulk concentrations of magnetizable material and is related to the grain size of the magnetic components (Rao *et al.,* 2010). The xlf graph shows four peak values indicating the higher concentrations of the magnetic minerals (Fig.4).The magnetic susceptibility of the samples ranges from $25.75 \times 10^{-6}$ to $183.00 \times 10^{-6}$ which is moderate.

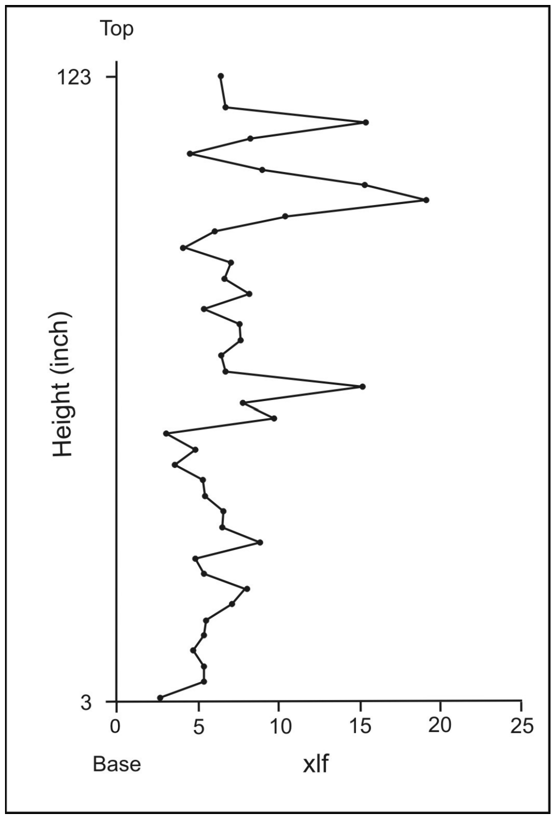


**Fig. 4:** Low Field Magnetic Susceptibility (xlf).

**Degree of Magnetic Anisotropy (P'):**

The glacio-lacustrine sediments being studied show degree of anisotropy ranging between 1.002 to 1. 328. However, for seven samples out of the total forty one, the values are relatively higher (between 1.124 to 1.328). It is also observed that the higher degree of anisotropy (Fig. 5) distributed at two levels also corresponds to higher *q* values and prolate nature of the fabric (described below). It is also observed that in some of the samples, the higher *P′* values correspond to the higher susceptibility and can be attributed to the presence of magnetite instead of deformation. However, tectonic overprinting is suggested for those samples, where the P’ values are higher and their corresponding susceptibility values are lower.

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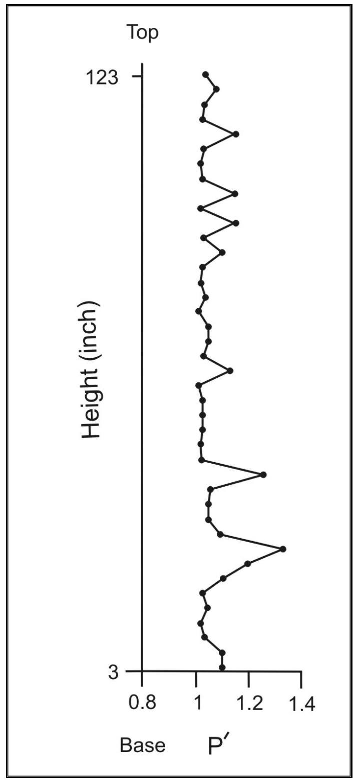


**Fig. 5:** Temporal variation of the degree of magnetic anisotropy (P').

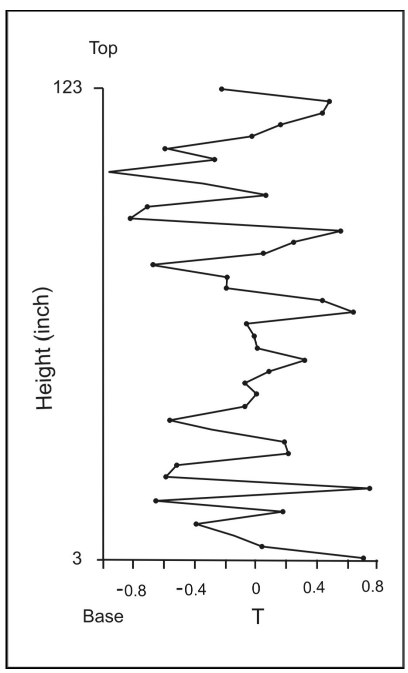


**Fig. 6:** Shape parameter *T* showing the prolate and oblate fabric in the samples.

**Shape Parameter:**

Normally, it is typical of the sediments to have a strong oblate magnetic fabric with shape parameter *T*> 0.1 (Sinha *et al.,* 2009). While determining the shape parameters of 41 samples collected from the 123 inches deep pit profile, it was found that 27 samples out of 41 have *T* values greater than 0.1 representing a strong oblate fabric. Fourteen samples in total have a typically strong prolate fabric with *T* values less than -0.1 (Fig. 6).

**Ellipsoidal Shape Factor:**

Another significant parameter which helps in discriminating between the depositional and the tectonic fabric is the *q* factor. It is determined as :

$$q = (K_1 - K_2)\,(K_1 + K_2)\,/\,2 - K_3$$

During the present study, the *q* factor values range from 0.036 to 1.588. The values less than 0.7 are indicators of undeformed sedimentary fabric while those having values higher than 0.7 suggest the imprints of neotectonics activity over the primary fabric (Sinha *et al.,* 2009). In the present study, there are two sets of samples at a depth of 120 to 100 inches and again at a depth of 40 to 20 inches show higher *q* values thereby indicating a prolate fabric (Fig. 7).

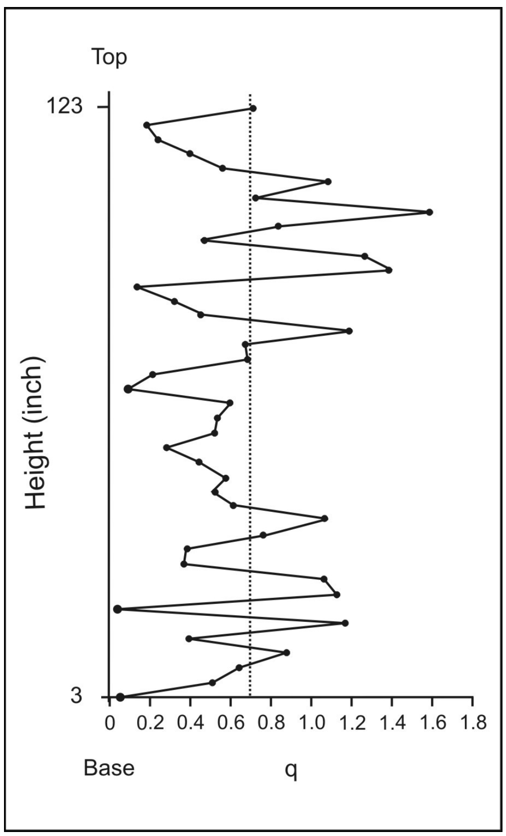


**Fig. 7:** Shape factor *q* showing the Tectonic and sedimentary fabric.

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**Flinn Plot:**

This plot between the magnetic foliation (*F*) and the magnetic lineation (*L*) shows the distribution of samples in the prolate and the oblate regimes (Fig. 8). In the present study it is observed that an appreciable number of samples fall in the prolate regime, thereby indicating the development of secondary (tectonic) fabric. The *L / F* values > 1 indicate a prolate fabric while those < 1, indicate an oblate field.

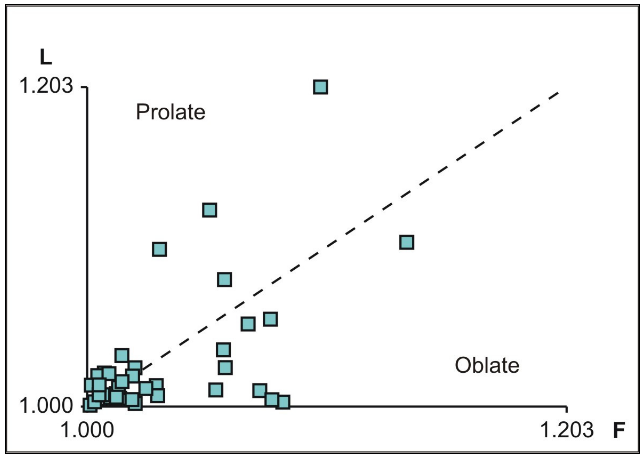


**Fig. 8:** The L/F plot showing thesamples in oblate and prolate fields.

## Discussion and Conclusions

Like other parts of Himalaya, the present area of investigation is also under the influence of neotectonic activity. The neotectonic activity in the area is well documented by the occurrence of a number of seismic events in the form of earthquakes in recent years *viz.*, Uttarkashi earthquake, 1991 and Chamoli earthquake 1999 (Rajendran *et al.,* 2000). The area comes under the Zone IV in the seismic zonation map of India (1996). The present study area is bound by two well know fault systems *i.e.* by Trans-Himadri Fault on the northern side and Pindari Thrust on the southern side (Valdiya and Goel, 1983). Moreover, the region is dissected by a number of smaller faults and thrusts, many of which may be active. The unconsolidated glacial till deposits are highly fragile and respond immediately to the slightest of the tectonic disturbances. Such terrains can thus be considered as one of the best repositories for qualitative as well as quantitative assessment of the process of rejuvenation. The present attempt to date some of the glacial deposits and correlating them with the morphotectonic evidences has helped us in bracketing and establishing chronology of such episodes to some extent. AMS studies to infer the imprints of active tectonics in a glaciated terrain are being attempted for the first time, although it has been effectively used for various other depositional fabrics. The rotation of the mineral fabric is the result of the various forces like gravity, Earth's magnetic field, hydrodynamic forces and tectonic stress acting during the formation indicating eventual geological history of the area. All of these act according to their own direction and tend to orient the grains, based on shape and size, according to preferential directions that correspond to the balance between the forces acting in each case. In the present analysis, the shape parameters *T* and *q* indicate that during the depositional history of this glacio-lacustrine deposit, there have been at least two phases, where the primary sedimentary fabric has been overprinted by secondary tectonic fabric. It is also observed that during these phases of deposition, the degree of anisotropy ($p'$) has also shown an appreciable increase. In order to further validate the data, AMS studies on other profiles are being carried out. Dating of some of the samples is being planned to establish a chronology of neotectonics events.

The impact of active tectonics is also evident by the presence of a number of geomorphic features like the skewed fans, inclined glacio-lacustrine beds, asymmetrical fluvial terraces and river entrenchment.

***Acknowledgements:*** Authors are thankful to the Head of Department, Centre of Advanced Study in Geology, University of Lucknow, for providing working facilities and to the anonymous reviewers for important suggestions that helped in improving the quality of the manuscript. Thanks are also due to Department of Science and Technology, Government of India, New Delhi, for funding the project vide project no.ESS/91/29/2004.

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**Table- 1:** Anisotropy of magnetic susceptibility data for the oriented samples collected from 11 feet deep pit at 2 kms upstream of Pindar River from Phurkia.

| Sample No. | L | F | P’ | T | q |
|---|---|---|---|---|---|
| 1 | 1.016 | 1.015 | 1.031 | 0.035 | 0.705 |
| 2 | 1.011 | 1.054 | 1.07 | 0.669 | 0.186 |
| 3 | 1.004 | 1.019 | 1.025 | 0.619 | 0.231 |
| 4 | 1.006 | 1.012 | 1.019 | 0.349 | 0.392 |
| 5 | 1.055 | 1.007 | 1.138 | 0.161 | 0.556 |
| 6 | 1.021 | 1.009 | 1.031 | 0.387 | 1.069 |
| 7 | 1.008 | 1.007 | 1.014 | 0.064 | 0.728 |
| 8 | 1.014 | 1.002 | 1.017 | 0.769 | 1.588 |
| 9 | 1.081 | 1.058 | 1.144 | 0.157 | 0.847 |
| 10 | 1.006 | 1.010 | 1.016 | 0.262 | 0.455 |
| 11 | 1.100 | 1.031 | 1.139 | 0.519 | 1.255 |
| 12 | 1.020 | 1.004 | 1.026 | 0.627 | 1.376 |
| 13 | 1.010 | 1.073 | 1.092 | 0.750 | 0.138 |
| 14 | 1.005 | 1.014 | 1.020 | 0.445 | 0.325 |
| 15 | 1.005 | 1.009 | 1.014 | 0.255 | 0.460 |
| 16 | 1.021 | 1.007 | 1.030 | 0.492 | 1.196 |
| 17 | 1.003 | 1.003 | 1.006 | 0.004 | 0.665 |
| 18 | 1.019 | 1.019 | 1.039 | 0.004 | 0.679 |
| 19 | 1.007 | 1.030 | 1.039 | 0.621 | 0.213 |
| 20 | 1.002 | 1.020 | 1.025 | 0.824 | 0.093 |
| 21 | 1.052 | 1.068 | 1.124 | 0.126 | 0.583 |
| 22 | 1.001 | 1.001 | 1.002 | 0.179 | 0.517 |
| 23 | 1.008 | 1.012 | 1.021 | 0.197 | 0.506 |
| 24 | 1.004 | 1.013 | 1.019 | 0.510 | 0.281 |
| 25 | 1.006 | 1.011 | 1.017 | 0.272 | 0.448 |
| 26 | 1.006 | 1.007 | 1.013 | 0.118 | 0.569 |
| 27 | 1.007 | 1.010 | 1.018 | 0.190 | 0.511 |
| 28 | 1.104 | 1.135 | 1.254 | 0.122 | 0.607 |
| 29 | 1.032 | 1.015 | 1.049 | 0.371 | 1.055 |
| 30 | 1.025 | 1.020 | 1.045 | 0.097 | 0.767 |
| 31 | 1.013 | 1.029 | 1.044 | 0.372 | 0.376 |
| 32 | 1.025 | 1.580 | 1.087 | 0.398 | 0.366 |
| 33 | 1.203 | 1.099 | 1.328 | 0.325 | 1.061 |
| 34 | 1.125 | 1.052 | 1.188 | 0.399 | 1.118 |
| 35 | 1.003 | 1.083 | 1.098 | 0.932 | 0.036 |
| 36 | 1.014 | 1.005 | 1.020 | 0.461 | 1.155 |
| 37 | 1.011 | 1.025 | 1.037 | 0.364 | 0.384 |
| 38 | 1.008 | 1.005 | 1.013 | 0.203 | 0.863 |
| 39 | 1.012 | 1.013 | 1.025 | 0.046 | 0.63 |
| 40 | 1.036 | 1.058 | 1.096 | 0.226 | 0.497 |
| 41 | 1.004 | 1.078 | 1.094 | 0.891 | 0.058 |

Note: F - Magnetic foliation, L - Magnetic lineation ($K1/K_2$), P' - Corrected measure of degree of anisotropy of the susceptibility ellipsoid, T - Shape parameter , q – Shape factor