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The relationship between tectonic stresses, joint patterns and landslides in the higher Indian Himalaya

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ABSTRACT

Tectonic stresses play a major role in the evolution of the present day landscape in the higher Himalayas. One of the principal geological manifestations of these stresses is the spatial orientation of joints and fractures. In this study these planar features and the stresses were correlated with landslides. It is observed that the direction of failure planes of landslides is concentrated either towards minimum stress axis σ_3 or along the intermediate stress axis σ_2 but never along the maximum stress axis σ_1.

The results provide the first rational basis towards the relationship of stresses, joint patterns and landslides in the Himalaya and have laid the foundation for further work on the stress – magnitude relationship of landslides for the region.

INTRODUCTION

Landslides are common in the higher Indian Himalayan Mountains. The context for landslides has been extensively studied (Haigh 1988; Hewitt 1988; Bartarya and Valdiya 1989; Pachauri and Pant 1992; Gerrard 1994; Owen et al. 1995; Panikkar and Subramanyam 1996; Gupta 1998; Shroder and Bishop 1998; Virdi et al. 1998). This research has attempted to interpret the various exogamic processes responsible for the development of landslides, the consequences of their occurrence and their mitigation, and also focussed on landslide hazard zonation (Gupta and Joshi 1990; Choubey et al. 1992; Gupta et al. 1993). The influence of tectonics or crustal stresses on landforms has long been recognised (Ollier 1981; Embleton 1987), particularly with respect to scarps (Bull and McFadden 1977), alluvial fans (Hooke 1972) and landslides (Ai and Scheidegger 1984; Scheidegger and Ai 1986; Harash and Bar 1988; Alexander and Formichi 1993), both at continental and regional scales.

Although previous studies in other parts of the world have demonstrated the relationship between tectonic stresses and landslides, no research has been undertaken into the nature of such relationships in the Himalaya. This paper examines this relationship by investigating an area with a high frequency of landslides in the Satluj valley between 77°57´and 78° 25´E longitude and 31° 27´ and 31° 40´ N latitude (Fig. 1).

Hypotheses

Tectonic stresses play a major role in shaping the topography of mountainous terrain (Ollier 1981; Embleton 1987). One of the principal geological manifestations of these stresses is the pattern of joints in the rocks, which can be observed at the surface. Studies have shown that the orientation of valleys and drainage networks is often closely related to these discontinuities in the crust (Scheidegger 1980; Abrahams and Flint, 1983; Pohn 1983).

It is hypothesised that the directions of these tectonic stresses significantly control the orientation and forms of failure planes in the landslides. Two types of influence are postulated:

i) Direct influence in which the slip directions of landslides are mostly directed towards the minimum or the intermediate principal stress directions, or across the maximum principal stress direction.

ii) Indirect influence in which most of the slip planes of landslides are along the joint directions that are the product of these tectonic stresses.

The Coulomb criterion suggests that shear joints can be used to estimate the orientation of the principal tectonic stresses operating in the area (Twiss and Moores 1992). The spatial orientation of these joints indicates the directions of the principal stresses operative during the compressional regimes. The concept used for the calculation of the stress direction is that shear joints are initiated in co- axial stress regimes as a pair of conjugating planes and, when subjected to compression, the rocks yield along the conjugated planes that intersect along the intermediate stress axis σ_2, while the acute angle between them bisects the principal stress axis σ_1 (Ramsay and Huber 1987) (Fig. 2).

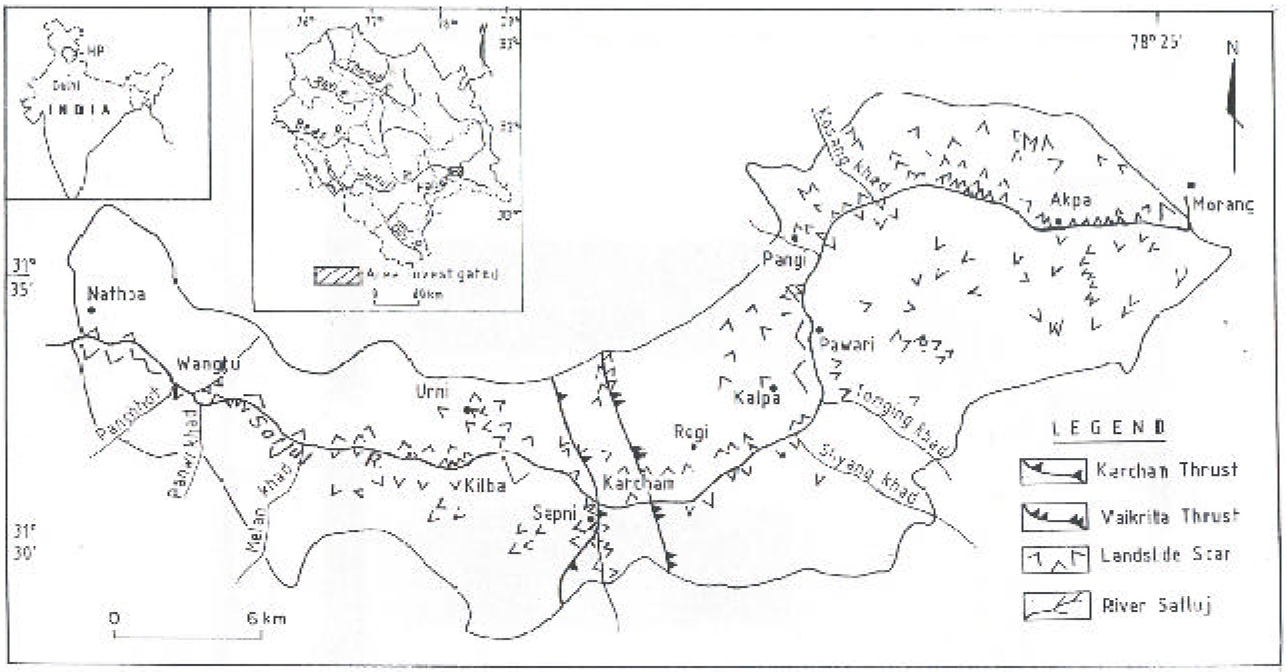

Fig. 1: Location map of the area, showing the spatial distribution of mass movement in study area

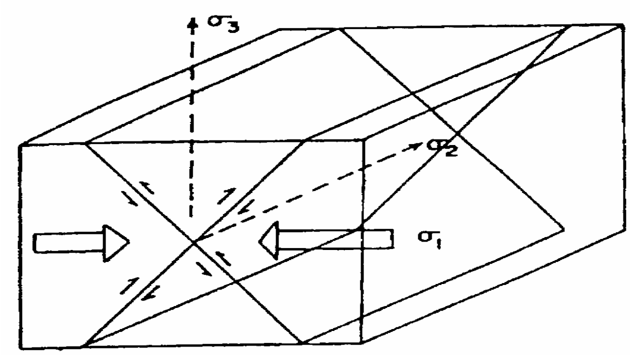

Fig. 2: Model diagram indicating direction of principal stresses with respect to the intersection of conjugated joint planes

This study relates the tectonic stresses and joint orientations to the failure planes of landslides.

GEOLOGICAL AND GEOMORPHOLOGICAL CHARACTERISTICS OF THE AREA

The study area cuts across the entire Higher Himalayan sequence, and is made up of a thick succession of medium- to high-grade metasediments (the Wangtu Gneissic Complex, and the Vaikrita and Haimanta Groups) and their sedimentary cover of the Tethyan sequence. These have been intruded by granites of various ages. The geological setting of this part of the valley has been studied in detail by Sharma (1976), Sharma (1977), Tewari et al. (1978), Bassi and Chopra (1983), and Kakkar (1988). Figure. 3 shows the distribution of major geologic units and tectonic features. Broadly, the area can be divided into four lithotectonic units separated by the Karcham Thrust, the Vaikrita Thrust, and the Tethyan Thrust. All these thrusts trend NNW–SSE or NW–SE, more or less parallel to the trend of the regional foliation.

Wangtu Gneissic Complex

The Wangtu Gneissic Complex comprises a thick sequence of augen gneisses, banded streaky gneisses and bands of amphibolites. There is a profuse emplacement of granitic and aplitic bodies in these gneisses, near the Wangtu where veins and sheets of pegmatites have also been intruded in an anastomosing pattern. Bands of amphibolites with a thickness of 10–20 m are also common. The rocks near the Wangtu and Nathpa dip due NNE and NE with slight variation. The rocks are highly folded with the fold axis trending E–W and plunging due east or northeast. The general strike rotates from NW–SE with northeasterly dip around Nathpa to almost N–S strike with easterly dip near Urni. The easterly dip continues beyond Karcham. The dips vary between 30^o and 40^o, occasionally exceeding 45^o.

Karcham Group

The Karcham Group is characterised by a different suite of metasedimentary rocks, and overlies the Wangtu Gneissic Complex along the Karcham Thrust, which is marked by a 1 m thick mylonitic zone. The dip of the shear zone is concordant with the foliation of the underlying gneisses and overlying quartzite, respectively. It consists of a 50 m thick, hard, massive, white, vitreous and brown quartzite band at the base followed by 200–300 m thick garnetiferous mica schist interbedded with micaceous quartzite bands (2 to 5 m thick). At a few locations, such

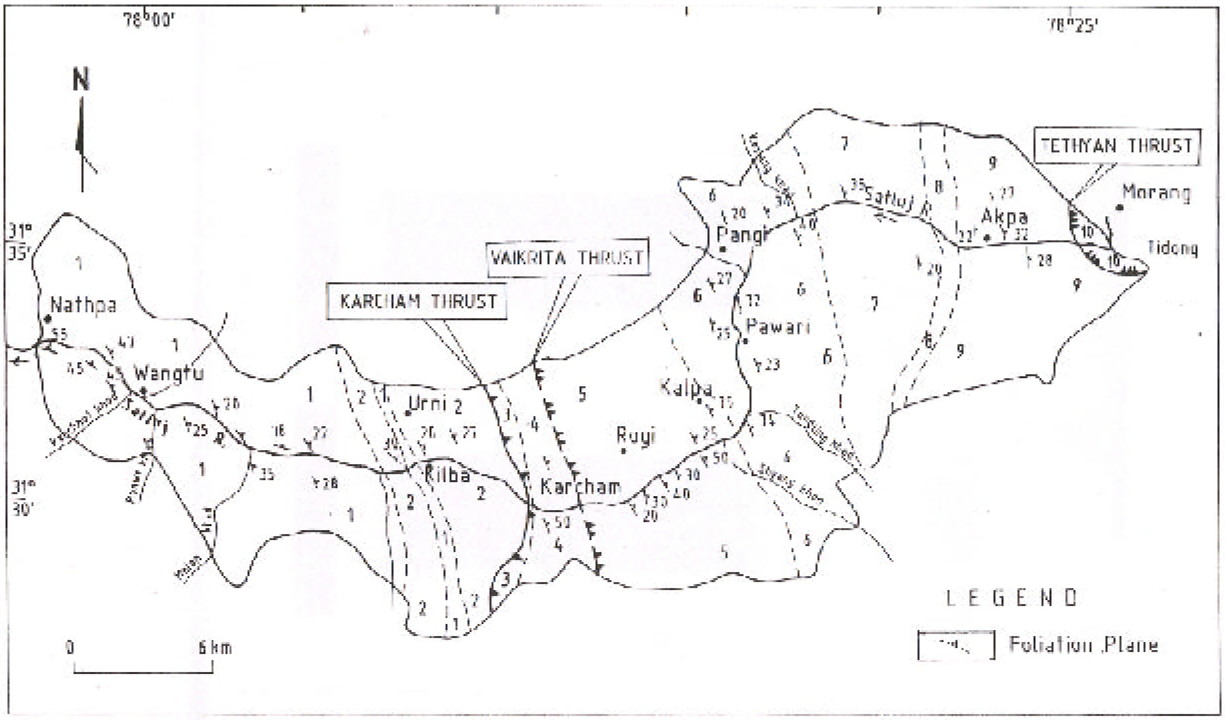

Fig. 3: Geological map of the area. 1 and 2: Finely banded gneisses with pegmatites belonging to the Wangtu Gneissic Complex (WGC). 3 and 4: Quartzite and interbedded with gernetiferous mica schist, graphitic schist and amphibolite belonging to the Karcham Group. 5, 6, 7, and 8: Psammitic gneisses, kyanite-bearing gneisses, granitic gneisses and quartz mica gneisses belonging to the Vaikrita Group. 9 and 10: Akpa granite and kyanite staurolite schist with quartz mica schist with amphibolites and some pegmatites belonging to the Haimanta Group

as near Karcham, small lensoid masses of amphibolites varying in thickness from 50 cm to 5 m are observed and can be traced for 50 to 75 m along the foliation plane. These represent basic rocks deformed and metamorphosed during the Himalayan Orogeny (Gupta 1998).

Vaikrita Group

The Vaikrita Group comprising the psammitic gneiss with quartzite bands, banded gneiss, coarse psammitic gneiss, granitic gneiss, and quartz-mica gneiss lies over the Karcham Group along the Vaikrita Thrust. The dip and strike of this thrust plane is in concordance with the dip and strike of the overlying and underlying rock foliation. The Vaikrita is intruded by a body of granite, called Akpa granite. It occurs as a 5–8 km thick sheet like intrusion.

Haimanta Group

Further eastwards, the Vaikrita Group is overlain by the Haimanta Group along the Tethyan thrust. This thrust is marked by 3 m of black crushed carbonaceous material. It trends NW-SE and dips at an angle of about 30° NE. The Haimanta Group consists of grey to purple quartzite, black carbonaceous phyllites, and quartz mica schist interbedded with amphibolite and calc schist. Some horizons containing big porphyroclasts of kyanite and staurolite occur toward the base.

Geomorphologically, the entire Upper Satluj Valley forms a highly immature topography with high relief and active erosional processes. Altitudes vary from 800 to 6050 m. Amongst the geomorphic processes, glacial and fluvial processes have played a dominant role in the terrain evolution in the past. Most of the processes currently acting in this area are denudational but at places local depositional processes also operate. The present landscape of the area has been carved by river Satluj and its tributaries.

The slopes are generally steep, with angles greater than 40°. The valley in the lower level is 'V' shaped and terminates into a narrow gorge along the Satluj River. The gorge section is nearly vertical to sub vertical and is about 200 to 300 m high. Most of the valley slopes consist of bare rock covered with scattered trees and bushes. However, in places, 5–10 m thick glacial and periglacial deposits are observed.

In the upper levels, the glaciers and snow-capped peaks are the prominent features. Fluvial terraces and the talus cones are the other geomorphic features lying along the valley slopes.

Joints are common and conspicuous in the entire area. Some of the joints can be traced for as long as 500 m along their strike (Fig. 4).

Fig. 4: A joint controlling the topography, which is located near village Wangtu and can be traced for 500 m long along its strike

Fig. 5: Urni rockfall showing wedge failure due to intersection of foliation and three sets of joints

LANDSLIDES IN THE STUDY AREA

Many landslides are found in the study area. The spatial distribution of these slides is shown in Fig. 1. Most of the landslides in the area occur naturally and frequently under the influence of a variety of factors. The triggering factors are mainly earthquakes and high precipitation in the forms of rainfall or snowmelt. The most common types of landslides are rock falls, rock, and debris slides, or a combination of both. Both planar and wedge failures are observed. Rock falls as well as rockslides are very hazardous and are densely distributed in the study area. They concentrate along zones of weakness, and are controlled by joints and fractures. They vary in size from a few hundred to many thousand cubic meters of material. However, many of the rock falls are relatively small, often with volume less than 500 m^3. Such small rock falls are common in the gorge section of the valley. The failure planes of most of these landslides are either along a dominant joint, or along the line of intersection of two or more joints. There are two major disastrous rock falls in the study area, namely the Urni and Nathpa rock falls.

Urni Rock fall

The Urni rock fall, located near village Urni, is about 500 m long, 40 m wide and about 7 m deep (Fig. 5). It is situated on a near vertical slope at the right-bank of Satluj river. The geology mainly consists of highly jointed gneisses belonging to the Wangtu Gneissic Group. This fall, which is a wedge failure, has occurred as a result of the intersection of four prominent vertical to sub vertical N–S, E–W and NE–SW trending joints, and a foliation joint trending NNW–SSE and dipping at 25^o ENE. Over many years, the episodic rock falls have created rapids in the Satluj river (Gupta and Virdi 2000).

Nathpa Rock fall

The Nathpa rock fall, which is located at the right-bank of the Satluj River near the village Nathpa is about 650 m long, 100 m wide and about 10–15 m deep (Fig. 6). This rock fall was triggered by heavy rainfall on 8th July, 1993. The overhanging cliff collapsed and deposited 1500 m^3 debris into the Satluj river, blocking its course for about 30 minutes, thus creating about 2000–2500 m long, 300–500 m wide, and

Fig. 6: A view of the Nathpa rockfall: the rockfall on 8 th of July, 1993, which blocked the course of the river Satluj for about 30 min.

Fig. 7: The tailrace tunnel (TRT) of an hydroelectric project situated about 600 m upstream of the Nathpa rockfall, is completely submerged.

25–30 m deep temporary lake. The rock type involved were highly fractured and sheared granitic gneisses of the Wangtu Gneissic Complex. Four sets of closely spaced fractures and joints broke the rock into small blocks. The tail race tunnel (TRT) of a hydroelectric project, situated about 600 m upstream, was completely submerged (Fig. 7).

METHODOLOGY

The study area has been divided into three zones on the basis of similar orientation of joints (Fig. 8). The zone (one kilometre on either side of the Karcham and Vaikrita thrusts) is analysed separately since these major thrusts have crushed the rocks and influenced the landslide activity in the area. This zone is hereafter called the thrust zone.

Stress analysis in zone I, II, and III has been undertaken by plotting the poles and the joint planes on the lower hemisphere of the equal area net. The poles in each zone were contoured to obtain maxima. Planes normal to these maxima were determined to get mean orientation of the dominant joints. In each zone, three to five maxima have been obtained. Of these, those two planes that make an angle of 60^o were considered to represent the mean orientation of conjugate sets of shear joints formed during the same phase of deformation (Badgley 1965). Inferences on the orientation of σ_1, σ_2 and σ_3 have been based on these conjugate sets of

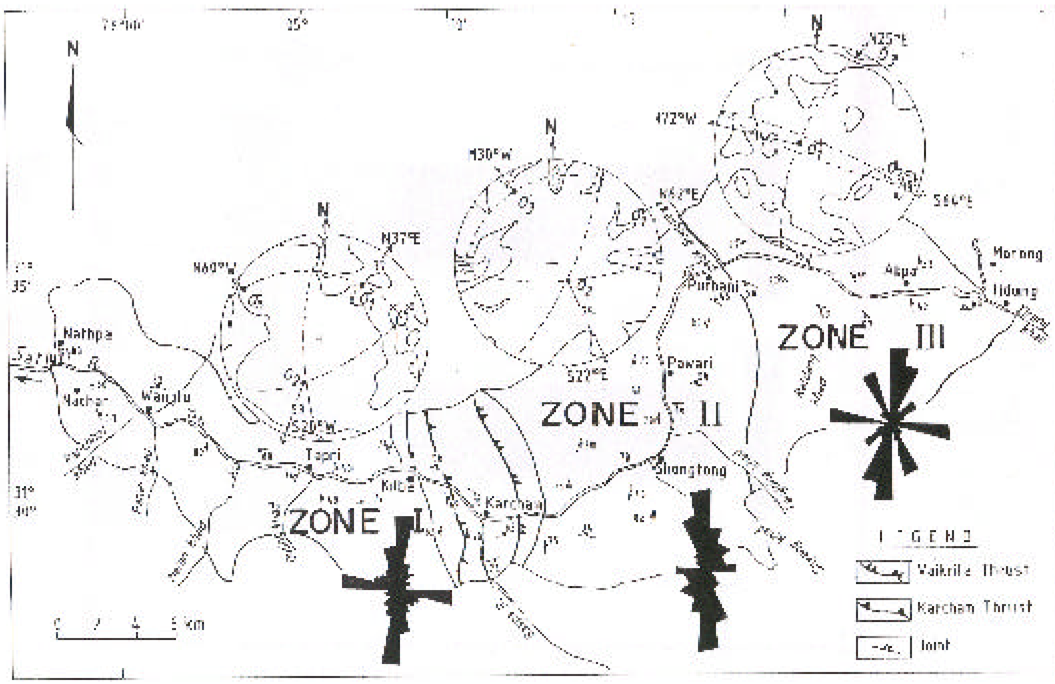

Fig. 8: Stereographic plots of joints along with their rose diagrams in zones I, II, and III

shear joints. The orientation of the intersection of these two planes denotes the σ_2 axis. σ_1 and σ_3 are given by the bisector of the acute and obtuse angle, respectively while the angle between σ_1 and σ_2 is 90^o (Fig. 2).

Data on the failure planes of landslides were directly collected from the field and presented in the form of rose diagrams for each zone (Fig. 9).

RESULTS

Figure. 8 presents the rose diagrams and the stereographic plots of joint orientation for zones I, II, and III. The figure clearly indicates four dominant sets of joints in the area. The joint set striking N-S is the most prominent in all the zones with a variation in strike from 10^o to 15^o. E-W trending sets are found in zone I and zone III. In addition zone III is characterised by NW–SE and NNE–SSW joint sets. Zone II is characterised by NNE–SSW and WNW–ESE trending joint sets. The orientation as well as the stereographic plot of joints in thrust zone have not been projected as the presence of two thrusts i.e. Karcham thrust and the Vaikrita thrust in a close vicinity in the area has rendered the rocks fragile and crushed.

The directions of σ_1, σ_2 and σ_3 in zones I, II, and III obtained using the equal area projections (Fig. 8) is presented in Table 1. Fig. 9 depicts the spatial orientation of failure plane of landslides in different zones. The quantitative estimation for all the failure planes of landslides in relation to joints and stress orientation for all the four zones is presented in Table 1.

The following observations and conclusions have been drawn by comparing these figures for different zones:

(i) It has been observed that in Zone I, 42% of slope failures occur due North and 23% due South (Fig. 9). These two directions are the prominent directions of joints. Thus, the failure planes of landslides in this zone are mainly joint controlled. Also, 27% of the failure planes found in this zone are mainly concentrated along the intermediate stress axis (σ_2) i.e. along S20W and the rest are mostly oblique to the maximum stress axis σ_1, i.e. N37E, (Fig. 9).

(ii) In Zone II, three prominent sets of joints present are N–S, WNW–ESE and NNE–SSW. The failure planes of landslides are also observed to be 31% to the East, 15% to the North and 23% to the South, indicating a strong correlation between the landslides failure and the major discontinuities present in this zone. Also, 48% of failure directions observed in this zone are concentrated towards σ_2, 8 % along σ_3 and the rest are oblique to σ_1 (Fig. 9).

(iii) In Zone III, four major joint sets are present, out of which 67% landslides are due south along N-S trending joint plane. This suggests that 67% of landslides in this zone are orthogonal to the maximum stress axis σ_1 and 12% along the minimum stress axis σ_3 (Fig. 9).

(iv) In thrust zone i.e. the area in the vicinity of Karcham and Vaikrita thrusts, 51% slip directions of landslide are East (Fig. 9). This is similar to the dip directions of these thrusts. The presence of the two thrusts in the close vicinity has made the area highly fractured, sheared, and pulverised. During the formation of these structures, a number of sheared zones of

Table 1: Spatial orientation of the failure planes of landslides in relation to joints and the stress directions

Zones	Joint Orientations	Stress Orientations			Failure planes of landslides in relation to		No of joints investigated	No of landslides present
		s_1	s_2	s_3	Joints	Stress orientations		
Zone I	N-S E-W	37/N37E	53/S20W	8/N60W	42 % along N 17 % due S	27 % along s_2 42 % across s_1	228	51
Zone II	N-S NW-SE NNE-SSW	3/N62E	75/S22E	19/N30W	31 % due E	56 % along s_2 8 % along s_3 Rest oblique to s_1	159	54
Zone III	N-S E- W NW – SE NNE - SSW	74/N72W	18/S64E	2/N25E	67 % due S 8 % due N	67 % across s_1 12 % along s_3	72	71
Thrust Zone	Crushed nature of rocks	51 % Slip directions of landslides are directed towards east i.e. the dip direction of the Vaikrita and the Karcham thrusts						31

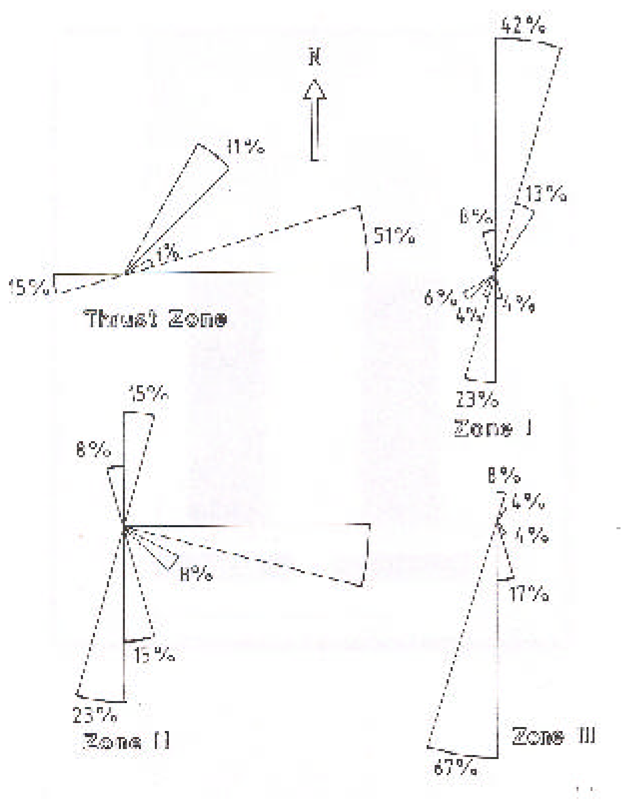

Fig. 9: Rose diagrams for the failures of landslides in different zones. The number represents the failure planes of landslides along that particular direction.

weakness have developed parallel to these thrusts and probably these planes of weakness are acting as the failure planes along which most of the mass movement has taken place.

DISCUSSIONS AND CONCLUSIONS

From the spatial inventory of mass movements (Fig. 1), it is clear that landslides are widespread in the study area. These mostly occur during or immediately after the rainfall or snowmelt. Though surface water is the main triggering factor for the initiation of landslides in the area, tectonic stresses prevailing in the area and the orientation of joints are the main controlling factors for the spatial distribution of landslides in the area.

Most of the landslides in the area occur along the dip direction of the planar features and the most conspicuous feature of the orientation of the slip direction of all the landslides is that there exists a systematic trend between tectonic stresses, orientation of joints, and slip directions of landslides. It is found that the slip direction of all the landslides is either along the minimum stress axis σ_3 or along the intermediate stress axis σ_2 but not in any case along the maximum stress axis σ_1. It is either orthogonal to the σ_1 or oblique to it (Table 1). These systematic trends found are correlated and explained with tectonic stress directions and the orientation of joints in the area. Thus, in the study area, the orientation of stresses appears to have performed a profound influence on the incidence of landslides.

The outcome of this work implies that in the mountainous terrain, particularly in the Himalayan region, which is very young and still active, inherent causes of landslides in conjunction with anthropogenic activity must be evaluated. This is well exemplified by the frequent occurrence of landslides in the region. Though on-spot geotechnical studies may be helpful to know the engineering properties of soils and rocks involved in the sliding phenomenon, the principal tectonic stress patterns and their orientation may be of use to know the dominant slip directions of landslides. Secondly, if the relationships between the stress and slip directions of landslide are established in other parts of the Himalayan terrain, analysis of the magnitude of stress with magnitude and frequency of slides may provide important additional information on landslide mechanisms. Equally, such relationship may predict changes in mass movement activities in the Himalayan region based on the stress patterns and vice versa.

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REFERENCES

Abrahams, A. D. and Flint, J. J., 1983, Geological controls on the topological properties of some trellis channel networks. Bulletin of the Geological Society of America, v. 94, pp. 80–91.

Ai, N. S. and Scheidegger, A. E., 1984, On the connection between the neotectonic stress field and catastrophic landslides. In: Proc. 27th International Geological Congress, Moscow, v. 6, pp. 180–189.

Alexander, D. and Formichi, R., 1993, Tectonic causes of Landslides. Earth Surface Processes and Landforms, v. 18, pp. 311–338.

Badgley, P. C., 1965, *Structural Methods for the Exploration Geologist*, Oxford Book Comp., New Delhi 280 p.

Bartarya, S. K. and Valdiya, K. S., 1989, Landslides and erosion in the catchment of the Gaula River, Kumaun Lesser Himalaya, India. Mountain Research and Development., v. 9(4), pp. 405–419.

Bassi, U. K. and Chopra, S., 1983, A contribution to the geology of Kinnaur Himalaya, Himachal Pradesh. Indian Journal of Earth Science, v. 10(1), pp. 96–99.

Bull, W. B. and McFaden, L. D., 1977, Tectonic geomorphology north and south of the Garlockfault, California. In: Doehring, D. O. (Ed.), Geomorphology in Arid Regions. Proceeding of the Eight Binghamton Symposium, Unwin – Hyman, London, pp. 115–138.

Choubey, V. D., Litoria, P. K., and Choudhari, S., 1992, Landslide hazard zonation in Uttarakashi and Tehri districts, U. P. Himalaya, India. In: David Bell (Ed.), Landslide Glissements de terrain. Proceeding. Sixth Interrnational Symposium on Landslides, Christchurch, New Zealand, Balkema, Rotterdam, pp. 911–917.

Embleton, C., (Ed.), 1987, Neotectonics and morphotectonics. Zeitschrift fur Geomorphologie Supplementband, v. 63, 240 pp.

Gerrard, 1994, The landslide hazard in the Himalayas: Geological control and human action. Geomorphology, v. 10, pp. 221–230.

Gupta, R. P. and Joshi., B. C., 1990, Landslide Hazard Zoning using GIS approach – a case study from the Ramanga catchment, Himalayas. Engineering Geology, v. 28, pp. 119–131.

Gupta, V., Sah, M. P., Virdi, N. S., and Bartarya, S. K., 1993, Landslide Hazard Zonation in the Upper Satluj Valley, District Kinnaur, Himachal Pradesh. Jour. Himalayan Geology, v. 4(1), pp. 81–93.

Gupta, V., 1998, Structure and Geomorphology of the Upper Satluj Valley, District Kinnaur, Himachal Pradesh, with special reference to landslides. D. Phil. thesis, HNB Garhwal University Srinagar (Unpublished).

Gupta, V. and Virdi, N. S., 2000, On the connection between landslides and nickpoints along the Satluj River course, Higher Himalaya, India. Zeitschrift fur Geomorphologie Supplementband, v. 122, pp. 141–148.

Haigh, M. J, 1988, Dynamic systems approaches to landslide hazard research. Zeitschrift fur Geomorphologie D. F. Sb, pp. 79–93.

Harash, A. and Bar, Y., 1988, Faults, landslides and seismic hazards along the Jordan River Gorge, northern Israel. Engineering Geology, v. 25 (1), pp. 1–15.

Hewitt, K., 1988, Catastrophic landslide deposits in the Karakoram Himalaya. Science, v. 242, pp. 64–77.

Hooke, R. LeB., 1972, Geomorphic evidence for late-Winsconsin and Holocene tectonic deformation, death Valley, California. Bulletin Geological Society of America. v. 831, pp. 2073–2098

Kakkar, R. K., 1988, Geology and tectonic setting of Central Crystalline rocks of southern part of Higher Himachal Himalaya. Journal Geological Society of India, v. 31, pp. 243–250.

Ollier , C. D., 1981, *Tectonics and Landforms*. Longman, London, 324 p.

Owen, L. A., Sharma, M. C., and Bigwood, R., 1995, Mass movement hazard in the Garhwal Himalaya: the effects of the 20th October 1991 Garhwal earthquake and the July–August 1992 monsoon season. In: McGregor, D. F. M., Thompson, D. A., (Eds.), *Geomorphology and Land Management in a Changing Environment*. Wiley, Chichester, U.K. pp. 69–88.

Pachauri, A. K. and Pant, M., 1992, Landslide Hazard mapping based on geological attributes. Engineering Geology, v. 31, pp. 81–100.

Panikkar, S. V. and Subramanyam, V., 1996, A geomorphic evaluation of the landslides around Dehra Dun and Mussoorie, Uttar Pradesh, India. Geomorphology, v. 15, pp. 169–181.

Pohn, H. A, 1983, The relationship of joints and stream drainage in flat lying rock of south central New York and northern Pennsylvania. Zeitschrift fur Geomorphologie N. F. v. 27(3), pp. 375–384.

Ramsay, J. G. and Huber, M. I., 1987, *Techniques of Modern Structural Geology. v. 2; Folds and Fractures*. Academic Press, London, 370 p.

Scheidegger, A. E., 1980, The orientation of valley trends in Ontario. Zeitschrift fur Geomorphologie N. F. v. 24(1), pp. 19 – 30.

Scheidegger, A. E. and Ai, N. S., 1986. Tectonic processes and geomorphical design. Tectonophysics, v. 126, pp. 285–300.

Sharma, K. K., 1976, A contribution to the geology of Satluj Valley, Kinnaur, Himachal Pradesh, India. Collques Internationaux du CNRS, v. 268, pp. 369–378.

Sharma, V. P., 1977, Geology of the Kullu-Rampur belt, Himachal Pradesh. Memoir Geological Survey of India, v. 106(2), pp. 235–403.

Shroder, J. F. and Bishop, M. P., 1998, Mass movement in the Himalaya: new insights and research directions. Geomorphology, v. 26, pp. 13 – 35.

Tewari, A. P., Gaur, R. K., and Ameta, S. S., 1978, A note on the geology of part of Kinnaur district, Himachal Pradesh. Himalayan Geology, v. 8(1), pp. 574–582.

Twiss, R. J. and Moores, E. M., 1992, *Structural Geology*. W. H. Freeman and Co., New York, 532 p.

Virdi, N. S., Sah, M. P., and Bartarya, S. K., 1998, Mass wasting its manifestations causes and controls: some case histories from Himachal Himalayas. *In:* Perspectives of Mountain Risk Engineering in the Himalayan Region (Eds.). D. K. Agarwal, A. P. Krishna, V. Joshi, K. Kumar and L. M. S. Pilani, Gyanodaya Prakashan, Nainital, pp. 111–130.