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Morphotectonics of mass movements on slopes

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ABSTRACT

The study describes the neotectonic effects on morphology of mass movements. Whilst the external (meteorological or seismic) processes are the immediate triggers of mass movements, their location and orientation is pre-designed by the tectonics of the area. The direction of mass movement is naturally in the direction down the slope of the valleys. If the latter are natural, they are parallel to the prevailing joints, which are shearing features of the neotectonic stress field. Most landslides, thus, are "shear"- or "wedge"-type failures. However, this is not true in the case of older valleys having been caused e.g. by nappe-edges emplaced much before the present-day resulting in "mountain fractures" and "valley closures", and particularly by artificial cuts: in such cases, slides occur mainly on faces oriented at right angles to one of the principal neotectonic stress directions. Evidently, the stability of the object is reduced in this case and slides occur more frequently than if the valleys or cuts run parallel to such principal stress directions. These findings are illustrated by specific examples from the Himalaya and the Alps.

INTRODUCTION

Surface mass movements cannot be considered separately from landscape development. The latter has been shown (Scheidegger 1987) to be governed by a series of principles of which the principle of antagonism is the most important. A landscape is the instantaneous result of the action of two antagonistic processes: the endogenic (originating inside the solid Earth) build-up processes and the exogenic (originating outside the solid Earth) denudation processes. The ongoing uplift is compensated by surface mass movements, generally directed downhill, which lead to a quasi-stationary state by a process-response mechanism (Carson and Kirkby 1972) "at the edge of chaos". One encounters tectonic elevation rates of the order of mm/a (km/Ma) in mountainous areas and corresponding exogenic denudation rates. Evidently, since the mountains have not become much higher in the last few million years (Ma), a substantial "flow" of mass must take place constantly over the landscape surface. This "flow" is represented by the surface movements discussed in this paper.

Another very important principle in landscape development is the principle of instability. By this concept, two things are implied. Firstly, one notices that many individual landscape elements are impermanent although their general character appears permanent. Secondly, one notices an additional aspect of the "instability": not only are the individual landscape elements impermanent, but also they move away from the equilibrium (e.g., a straight river becomes crooked, a rectilinear slope forms terraces, and a hole becomes bigger). The instability principle refers not only to the spatial aspects, but also the temporal ones. Once a deviation from a steady state occurs, this deviation reinforces itself so that the process (such as a sequence of landslides) evolves in spurts; their incidence is a stochastic time series with a fractal structure.

A third important principle of landscape evolution is that of tectonic pre-design: whilst exogenic processes are generally best described as stochastic, there is nevertheless a connection of their orientation structure with tectonic features: many geomorphic features are, in fact, *pre-designed* by the neotectonic stress field.

Significance of joint orientations

Joints are ubiquitously present in rocks in the form of small cracks or fissures. In outcrops they appear at first sight to present a chaotic pattern, but upon closer inspection, one generally discerns three distinct sets, one of which is sub-horizontal; the other two are steeply dipping and are oriented at right angles to each other. The sub-horizontal set corresponds to the rock layering; the steeply dipping (sub-vertical) ones are miniature shearing-fractures that have been caused by the neotectonic stress field (Scheidegger 1978).

A typical example of this pattern is represented by one of the outcrops used in this paper on the Rudraprayag side of the Kaliasaur landslide, shown here in Plate 1. The first subvertical set of joints runs (in the picture) from the lower left diagonally upwards to the upper right, the second set from the lower right towards the upper left, and the subhorizontal set is represented by the layering forming the base. A breakout niche has been formed between the first two (subvertical) sets.

Inasmuch as the regularities mentioned above are not absolute, they have to be determined statistically. This can be done non-parametrically by the inspection of a joint-pole density diagram: one represents each joint plane in an outcrop by its pole on an imaginary unit sphere around the outcrop and represents this sphere in an equal area projection. A "pole density diagram" is obtained if isolines are drawn for the density of pole-points on the unit sphere. Then, the "mean" directions of the joint sets are indicated by the pole-density maxima, which can be picked by visual inspection. These maxima present the "mean" directions of the corresponding joint sets.

A more accurate analysis is achieved by numerical statistical methods as described by Kohlbeck and Scheidegger (1977, 1985). The latter are based on the assumption that the joint poles belonging to one set (as defined above) correspond to a Dimroth (1963)- Watson (1970) distribution that, on a sphere, is the equivalent of a Gaussian distribution on a line. The Dimroth-Watson distribution is determined by 4 parameters. If x such distributions are superposed on a sphere, their integral must be equal to 1. For this reason, one does not need 4x parameters to determine x distributions, but only 4x-1. If one assumes the presence of three sets of joints in an outcrop, one needs 4x3-1=11 parameters to describe them. Usually, only the two subvertical sets are of interest, because they alone correlate with the tectonics of the area.

According to the above, two distributions require for their determination 4x2-1=7 parameters. Generally, every "measured value" has to be supported by 3 individual measurements; thus the determination of the directions of two sets of joints at an outcrop requires 3x7=21 joint orientation measurements. This may appear as a small number, but Kohlbeck and Scheidegger (1985) have given an explicit verification of this statement: if two individual sets exist at all at an outcrop, 21 measurements are indeed sufficient; taking more measurements only insignificantly increases the accuracy of the result. If no pattern of sets exists, i.e. if the joints are indeed randomly oriented, even hundreds of measurements do not result in definable orientation-maxima.

In turn, once the orientations of the principal joint sets have been determined, it is also possible to determine from there the orientation of the principal stress directions of the neotectonic stress field that has caused them (Kohlbeck and Scheidegger 1977, 1985). They are the bisectrices of the two subvertical joint sets; the smaller angle contains the maximum compression (P), the larger angle the minimum compression (T); however, if the intersection angle between conjugate joint sets is close to 90°, it is not possible to identify the smaller angle with certainty.

The calculations are normally carried out using dip directions and dip angles of the joints. However, for geological visualisations, strikes are of more immediate use. Thus, our further discussions will be in terms of strike directions and strike roses rather than in terms of dip directions and pole density diagrams.

In summary, joint orientation measurements allow one:

- to determine whether sets exist at all;
- to determine the ("mean") directions of such sets; and
- to investigate whether these directions are related to other geomorphologically important directions. If this is the case, then the corresponding geomorphological directions are, like those of the joint sets, most probably *neo*-tectonically pre-designed.

Slide types

Thus, joint orientations in an area may be reflected in landscape features. Thus e.g. valley directions and surface mass movements are correlated to them. If the latter are natural, they are parallel to the prevailing joints, which are shearing features of the neotectonic stress field. Such landslides are "shear"- or "wedge"-type of failures. However, this is not true in the case of older valleys having been caused e.g. by nappe-edges emplaced much before the present day (then the latter lead to "mountain fracture" and "valley closure"), and particularly by artificial cuts (Ai and Scheidegger 1984). In such cases, slides occur mainly on faces running at right angles to one of the principal neotectonic stress directions. In this case, slides occur more frequently than if the valleys or cuts run parallel to such principal stress directions.

One thus has to consider two fundamental types of slide: Those due to shearing fractures and those due to mountain fractures/valley closures. We shall illustrate these slide types by means of two characteristic examples from the Himalaya and the Alps.

SHEAR SLIDES

Shear- or wedge slides are characterised by a displacement direction at their surface, which is parallel to one or both of the conjugate subvertical joint strikes. Thus, the displacement my not be in the direction of steepest descent, or the slide may spread apart in the centre, forming a *wedge* whose edges move parallel to the joints. They are the most common types of slide and occur primarily in neotectonically active regions such as the Alps and the Himalaya. We shall discuss here a typical slide of this type that we studied in the Garhwal Himalaya.

Kaliasaur slide (the Garhwal Himalaya, Uttar Pradesh, India)

During a field trip arranged in 1998 by the Wadia Institute of Himalayan Geology into the Garhwal Himalaya devoted to inspecting slides (Field Guide by Sah and Bist 1998), it was possible to make a morphotectonic study of the Kaliasaur slide between Srinagar and Rudraprayag (location 78°50' E, 30°15' N; Plate 2 and Fig. 1). Joint orientations could be measured on outcrops at both sides of the slide, viz. towards Srinagar (Fig. 1, Location B) and towards Rudraprayag (Fig. 1, Location C). The results of evaluating the joints of these two outcrops according to the Kohlbeck and Scheidegger (1977) method are shown in Table 1 (the direction of tectonic pressure and tension direction are deduced from the strikes). The strike rose is shown in Fig. 2 (left). Furthermore, the Field Guide (Fig. 2 of Sah and Bist 1998) shows arrows indicating displacement directions, and the orientations of these directions can be measured and treated like joints. The corresponding trend rose is shown in Fig. 2 (right). It shows that there is really only *one* maximum that has also been calculated numerically by the Kohlbeck and Scheidegger (1977) method (Table 1).

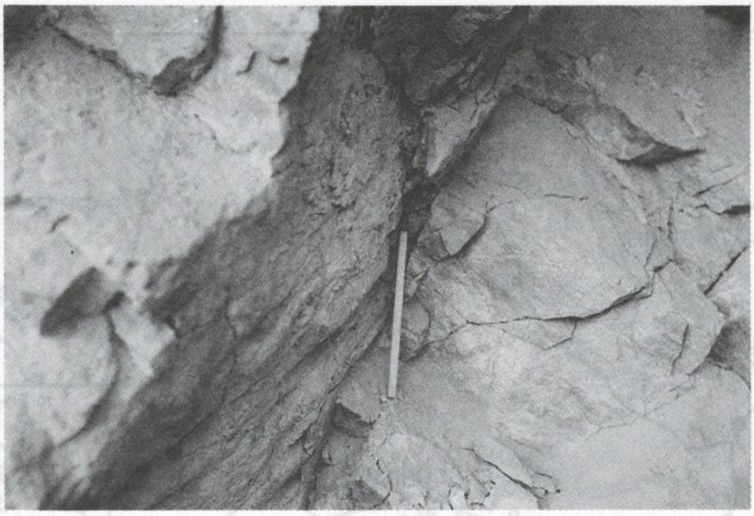

Plate 1: Typical outcrop with subvertical sets leading to a break-out niche: the outcrop is on the Rudraprayag-side of the Kaliasaur landslide; the first subvertical set of joints runs (in the picture) from the lower left diagonally upwards to the upper right, the second set from the lower right towards the upper left, and the subhorizontal set is represented by the layering forming the base. A break-out niche has been formed between the first two (subvertical) sets.

Plate 2: View of the Kaliasaur slide. Note the "wedge" morphology. This is a typical shear-slide.

Table 1: Evaluations for the Kaliasaur Landslide: strike directions of joints and trends of displacement

Feature	Number of measurements	Maxima of joint strikes or displacement trends		Angle (°)	Direction of tectonic pressure, P (°)	Tension direction, T (°)
		Maximum 1	Maximum 2			
Joints	36	157±12	65±29	88	21	111
Displacements	16	157±19				

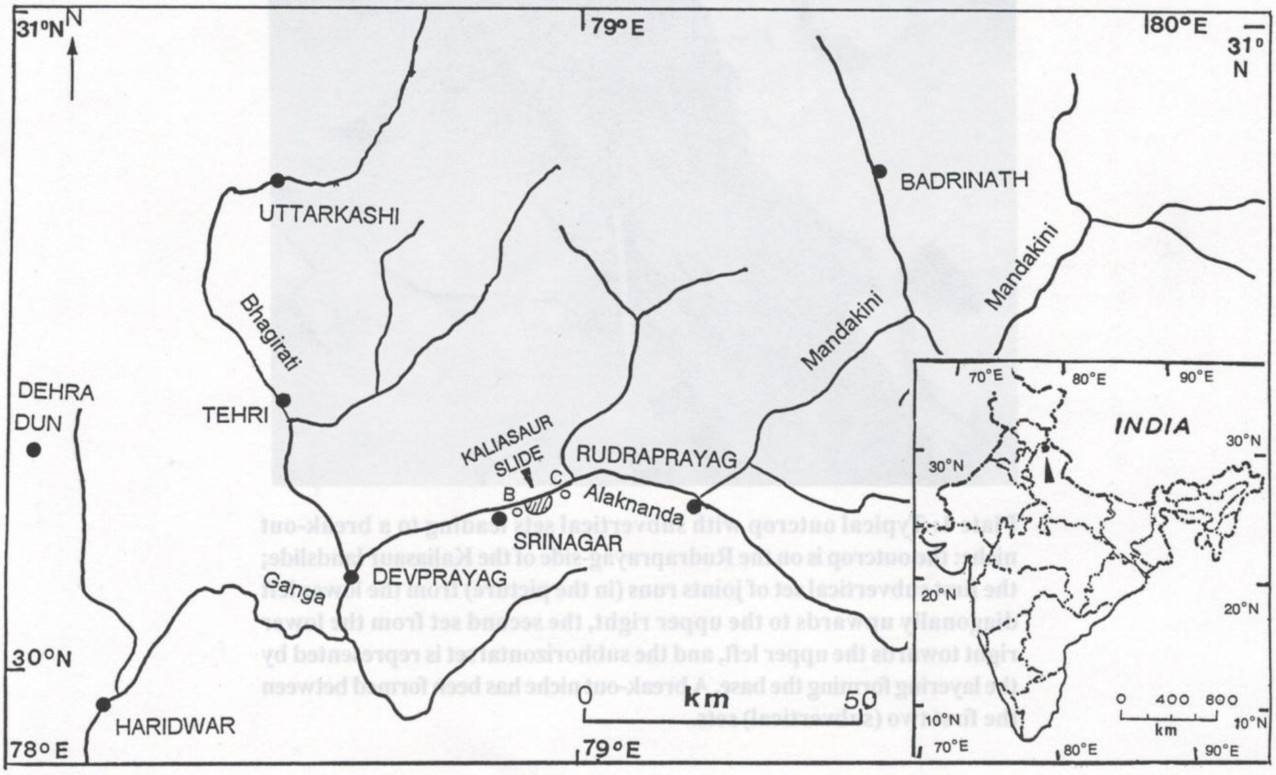

Fig. 1: Location of the Kaliasaur slide in the Garhwal Himalaya. Open circles: locations (B and C) of joint orientation measurement

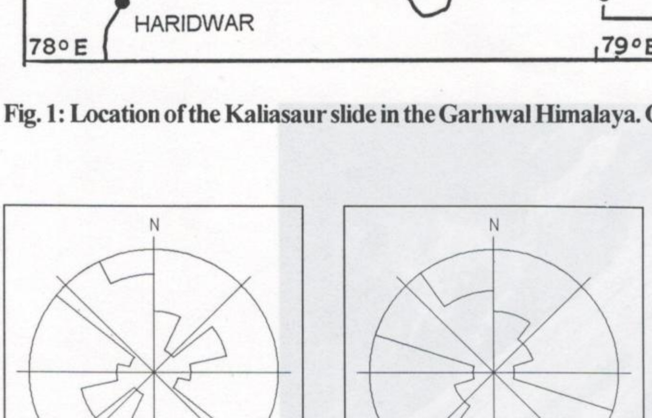

Fig. 2: Comparison of the rose diagrams of the joint strikes (left) and the displacement directions (right) around the Kaliasaur slide. Note that the displacement maximum coincides with one of the joint strike maxima: i.e. the motion is a shear motion along a joint surface as is typical of wedge-type or shearing slides.

It is seen that there is an excellent agreement between the maximum of the displacement directions and one of the joint strike maxima. This condition is indicative of shear- or wedge-type failure causing a slide and has been encountered in many parts of the world.

SLIDES AT MOUNTAIN FRACTURES AND ARTIFICIAL CUTS

As noted earlier, if a valley or slope-cut has been created *independently* of the neotectonic conditions, slides will preferentially occur on faces oriented normal to one of the principal tectonic stresses. This, incidentally, can be the tension (T) or the compression (P). The typical cases in nature occur in the form of "mountain fractures", where at the ledge of a ridge a "tensional fracture" (in the form of a ditch) is opening up, but at the bottom a slump-hump is formed which stands under pressure. This represents the classic morphology of a "mountain-fractures" above "valley-closures" below. We shall discuss a classic case of this type from the Swiss Alps.

Slide at La Frasse, Switzerland

In connection with a symposium on landslides in Lausanne, a landslide near La Frasse in the Canton of Vaud, Switzerland, was inspected. Plate 3 shows a view of the foot of this landslide, and its location is shown on the map in Fig. 3.

Geologically, the slide occurred in the Ultrahelvetic Flysch. The slope consists of flysch material and abuts (in the SE) against a wall of middle Triassic dolomite (Noverraz and Bonnard 1990), which forms the orographically

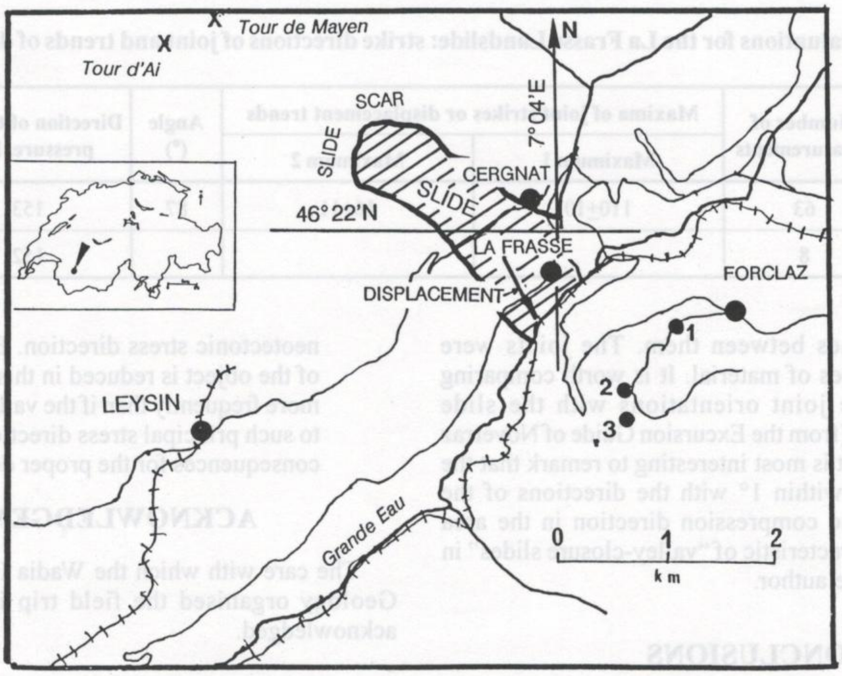

Fig. 3: Map of the slide area near La Frasse (canton of Vaud, Switzerland) with unstable area and locations of joint orientation measurements (black dots 1, 2, and 3) indicated

Plate 3: Photograph of the foot of the La Frasse slide, showing the flysch material piling against the dolomite wall forming the left bank of the (previously existing) Grande Eau River. This represents the typical morphology of a "valley closure".

left bank of the Grande Eau River. Plate 3 shows the flysch material abutting against the dolomite wall forming the left bank of the Grande Eau. This morphology is characteristic of "valley closure". The village of Cergnat was much affected by the mass movements as evidenced by the bridge of the village road needing constant repairs. The unstable area is also shown in Plate 3, and the Excursion Guide gives the velocities directed at N 152° E (Noverraz and Bonnard 1990).

Joint orientation measurements were made near la Forclaz on the opposite (SE) side of the Grande Eau valley (Locations 1, 2, and 3 in Fig. 3; Fig. 4). Ridges of conglomerate (Nagelfluh) descend downslope, embracing wedges of

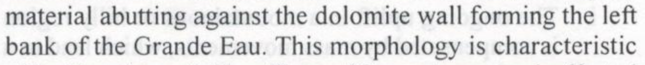

Fig. 4: Rose diagram of the joint strikes near La Forclaz (La Frasse area) compared with the displacement directions in the La Frasse slide. Note that the displacement maximum falls in between the joint strike maxima. This is again characteristic of valley closure slides.

Table 2: Evaluations for the La Frasse Landslide: strike directions of joint and trends of displacement

Feature	Number of measurements	Maxima of joint strikes or displacement trends		Angle (°)	Direction of tectonic pressure, P (°)	Tension direction, T (°)
		Maximum 1	Maximum 2			
Joints	63	110±10	16±11	87	153	63
Displacements	8				152	

calcareous sandstones between them. The joints were measured in both types of material. It is worth comparing the results of these joint orientations with the slide displacement vectors (from the Excursion Guide of Noverraz and Bonnard 1990). It is most interesting to remark that the slide motion agrees within 1° with the directions of the maximum neotectonic compression direction in the area (Table 2). This is characteristic of "valley-closure slides" in the terminology of the author.

CONCLUSIONS

Mass movements on slopes are part and parcel of the normal landscape development cycle about which the following statements can be made:

i. The ongoing uplift in a mountainous or hilly region is compensated by mass movements, which lead to a quasi-stationary state by a process-response mechanism.
ii. The mass movements *occur in spurts*; their incidence is a stochastic time series with a fractal structure.
iii. *The direction of mass movements is pre-designed* by the neo-tectonic stress-field. The latter also generates the *orientation* of the joints; hence the direction of the joints and the slide-motion directions are correlated. The direction of the mass movements is naturally in the direction down the slope of the valleys. If the latter are natural, they are parallel to the prevailing joints, which are shearing features of the neotectonic stress field. The landslides, thus, are "shear"- or "wedge"-type of failures. However, this is not true in the case of older valleys having caused e.g. by nappe-edges emplaced much before the present-day (then the latter lead to "mountain fracture" and "valley closure"), and particularly by artificial cuts. In such cases, slides occur mainly on faces running at right angles to one of the principal neotectonic stress direction. Evidently, the stability of the object is reduced in this case and slides occur more frequently than if the valleys or cuts run parallel to such principal stress directions. This has practical consequences for the proper design of artificial cuts.

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