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Petrologic and structural controls on geomorphology of prehistoric Tsergo Ri slope failure, Langtang Himal, Nepal

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Abstract

High relief (Δh up to 2600 m) and spatial orientation of discontinuities, such as leucogranitic intrusions, mylonitic and pseudotachylitic horizons and related ore structures, were the preparatory causal factors for the giant prehistoric Tsergo Ri landslide (High Himalayan Crystalline, Langtang Himal, Nepal). Other controlling factors include overthrusting, detachment faulting, and paleoseismics related to the Main Central Thrust (MCT) and Southern Tibet Detachment System (STDS), neotectonically generated structures, and predesigned form of the scarp (broken crest) and the direction of movement towards the WSW. Coherently displacement of several 10^9 m^3 materials caused frictional fusion. Landslide dynamics and specific morphologic conditions created four different types of sliding surfaces (in chronological sequence): (i) primary—at the basement, (ii) secondary—parallel or subparallel to (i), (iii) tertiary—vertical to (i) and (ii), and (iv) quarternary sliding surfaces—local variety of (iii). (Note: ordinal numeric terms are not in time-stratigraphic sense.) These planes represented the main discontinuities conducting different syn-event stresses in the sliding mass and for further landslide dynamics. Spatial difference and widespread distribution of sliding planes and sets of discontinuities all over the landslide area caused different classes of rock quality, which subsequently determined specific erosional processes within the landslide accumulation area. The subsequent glacial and fluvial erosional processes were controlled by the correlating preexisting lithotectonic patterns, the hyalomylonitic and/or breccious sliding planes and the recent morphologic features or shapes of Tsergo Ri. (i) The SE part is gradationally brecciated to the top and includes Tsergo Ri itself. The residual mass of the bulk has been eroded almost isometrically as far as the primary sliding plane crops out along the intact gneissic basement. Differences in rock quality along a horizon of secondary sliding planes indicate a steplike break in the relief after the last main glaciation. (ii) The earlier-halted NW part still preserved micromountainous shape of compact sliding blocks (Phushung I and II, Kyimoshung), separated by landslide-dynamic-triggered faults (tertiary and quarternary sliding planes). Primary and secondary sliding planes, almost covered by Holocene sediments, produced an insignificant morphology. (iii) The highest brecciated strike–slip fault, generated during collision with the obstacle of Pangshungtramo Peak in the southwest, is the deeply eroded Dranglung Chu valley, which has been kept morphologically active in a major way until recent times. (iv) Except for the collision obstacle of Pangshungtramo Peak with recent semi-active erosion and a small secondary rockslide (block of Tsangbu) north of it, all surrounding parts show typical features of high altitude erosion. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: petrologic control; structural control; geomorphology; Tsergo Ri; landslides; petrologic controls; structural controls; erosional processes; Himalaya; Nepal

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1. Introduction

The prehistoric Tsergo Ri landslide (fission-track age 'some' 10^4 years) has rock fusion along the sliding surfaces (Scott and Drever, 1953; Masch and Preuss, 1977; Heuberger et al., 1984) which enables good conditions for studying the effects of giant mass movements in a crystalline environment. Investigation of the landslide from the view of engineering geology (Weidinger, 1992; Weidinger and Schramm, 1995a,b; Schramm and Weidinger, 1996; Weidinger et al., 1995a), preparatory causal factors (Weidinger et al., 1995b, 1996) and mountain hazard geomorphology (Ibetsberger, 1993, 1995, 1996a,b; Ibetsberger and Madhikarmi, 1995) led to the interpretation of the morphological evolution of the landslide deposit and the surroundings as the result of preexisting lithotectonic structures, landslide dynamics (sliding planes) and subsequent erosional processes of the regional main glaciation (Heuberger and Ibetsberger, 1996) and the local high monsoonal precipitation. The basal and internal sliding planes of the landslide mass were mainly focused around these aspects, in addition to tectonic structures and lithology.

Numerous landslide deposits provide evidence that internal structures and movement planes are controlling specific forms and post-event characteristics (Erismann et al., 1977; Preuss, 1986; Abele, 1974, 1994). Could the same relationship develop a heavily eroded deposit such as Tsergo Ri landslide? The consequences for the interpretation of landslide dynamics and movement processes are shown in the following study as a review of the most typical features dealing with this problem.

2. Regional geologic setting and local lithology

The Langtang valley runs about 15 km south of the South Tibetan Detachment System (STDS), which is exposed near the Gyrong region (Macfarlane, 1993). It bends from almost a N–S direction in the upper parts to a more or less E–W direction in the lower parts, traversing the Langtang Migmatite Zone (Kyangjin and Langshisa Unit), the hanging wall of the High Himalayan Crystalline Sequence (Reddy et al., 1992). This sequence, locally composed of gneisses, migmatites (dipping 20°–30° to NE), and young, partly discordant leucogranitic dikes (dipping SW to W) forms the bedrock of Tsergo Ri landslide and surroundings (Fig. 1). The landslide event (Weidinger et al., 1995b, 1996) was caused by the primary lithologic composition, the tectonic pattern (mylonites and pseudotachylites because of overthrusting and paleoseismics associated with the Main Central Thrust (MCT) further south and/or the STDS further north) and mineralogic features such as ore structures related to leucogranites.

Mechanical and weathering properties of the locally outcropping gneisses, migmatites and granites only differ slightly. No evidence exists for selective weathering of generally different lithologies. Although granites react more brittly to dynamic stress, receiving primary erosion after the shattering landslide event, the partly biotite-rich migmatites and gneisses are susceptible to weathering and erosion as well. Assuming almost uniform lithology and more or less equal morphodynamic parameters in and around the investigated area, most of the morphologic shapes would seem to be the results of regional tectonic and local structures (sliding planes) of the landslide mass.

3. Tectonic structures

Preexisting paleo- and neotectonic structures in the upper Langtang valley controlled the broken crest of Tsergo Ri landslide and directed movements towards the WSW. The paleorelief, with respect to mountain crests and valleys, depends upon orogenic processes (overthrusting, paleoseismics) that relate the main strike (NW to SE) due to primary foliation (slightly towards NE). Some glaciers (Phrul Rangtshan Tsang, Ledrub–Lirung Tsang) were, and are partly still, using this natural pathway. Neotectonic structures with opposite dips towards SW to W, parallel or subparallel to leucogranitic intrusions and mylonitic horizons (Weidinger et al., 1995b, 1996), as well as those steeply SE dipping (SE ridge of Pangshungtramo Peak, SE flank of Dragpoche), forced the scarp into its recent curved shape, as well

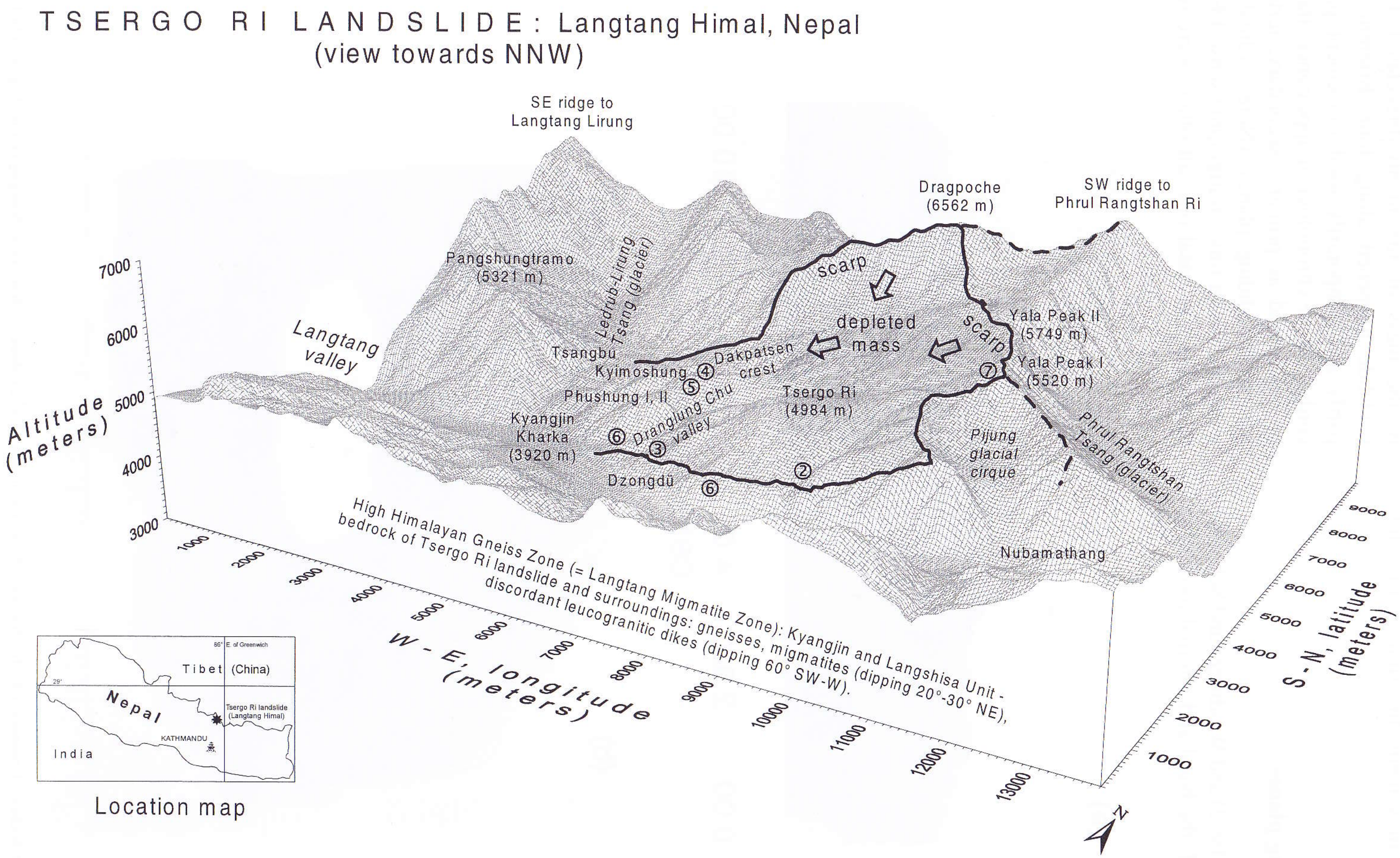

Fig. 1. Location map and surface plot of the Tsergo Ri landslide area. The solid line delimits the scarp, the depleted mass and the zone of accumulation. The dashed line shows a supposed former prolongation of the scarp towards NE and SE (subsequently eroded). Arrows indicate the main directions of movement. Circles with numbers (2–7) refer to Figs. 2–7.

as controlled the movement direction of the slide (Fig. 1).

4. Types of sliding planes

As Weidinger (1992) and Weidinger and Schramm (1995a,b) reported, the basal and internal movement of the mass of the highly brecciated Tsergo Ri landslide happened along four different types of partly and temporarily used movement paths. According to the chronological appearance, these are to be considered as primary, secondary, tertiary, and quarternary sliding planes. (Note: ordinal numeric terms are not in time-stratigraphic sense.) Except for the primary or basal one, all others were utilized in

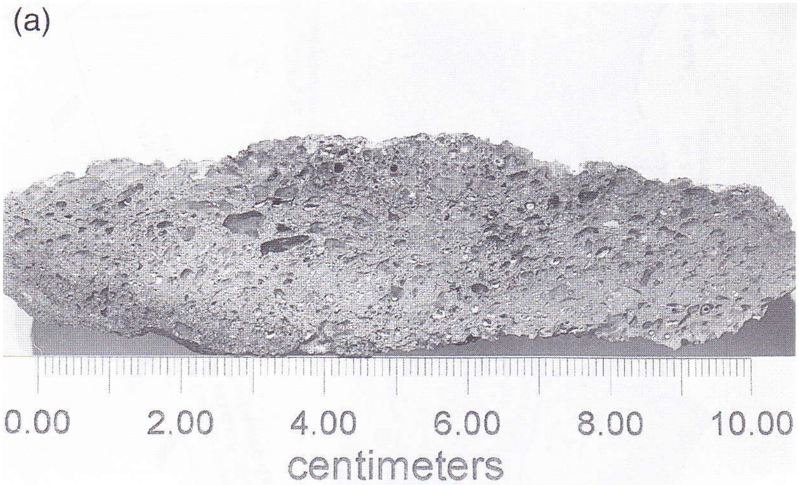

Fig. 2. (a,b) Lenticular bodies of pumice-like hyalomylonite as inclusion of microbreccia horizons. Sample (b) with gas-bubble, elongated because of sliding direction. Location: secondary sliding plane, Tsergo Ri S-flank, altitude 4540 m (see Fig. 1).

the movement as internal slip planes. Despite this cause, all of them controlled the subsequent morphological overprint after the landslide event, as well as the shape of the recent accumulation area.

Primary or basal sliding planes represent the boundary between the basement of the landslide (gneisses) and the mass of the highly brecciated landslide (migmatites, granites). In the Tsergo Ri landslide area, Masch and Preuss (1977) and Heuberger et al. (1984) described frictional fusion along the base, creating hyalomylonite and microbreccias. Besides these investigations, Weidinger et al. (1995b, 1996) noticed that preexisting lithotectonic fault planes (slickensides, mylonites/ultramylonites and pseudotachylites), lithotectonic structures (discordant leucogranitic intrusions and related sulfidic ore structures) also functioned as preparatory causal factors, having been partly used as primary sliding planes, too.

Secondary sliding planes developed internally (i.e., within the highly brecciated landslide mass) parallel or subparallel to the primary sliding planes. Although mineralogy and shape are almost similar to the primary sliding planes, the position and slight differences in genesis (less hyalomylonite because of slower and not uniform movement of the landslide mass) allow differentiation between failure planes in the Tsergo Ri landslide area (Weidinger, 1992; Weidinger and Schramm, 1995a,b). The first type, occurring in the SE part of the deposit, in the S flank of Tsergo Ri, is exposed as a sequence of microbreccious horizons partly including lenses, balls or irregular bodies of pumice-like hyalomylonite (Fig. 2a,b). The second one, in the NW part of the deposit (W

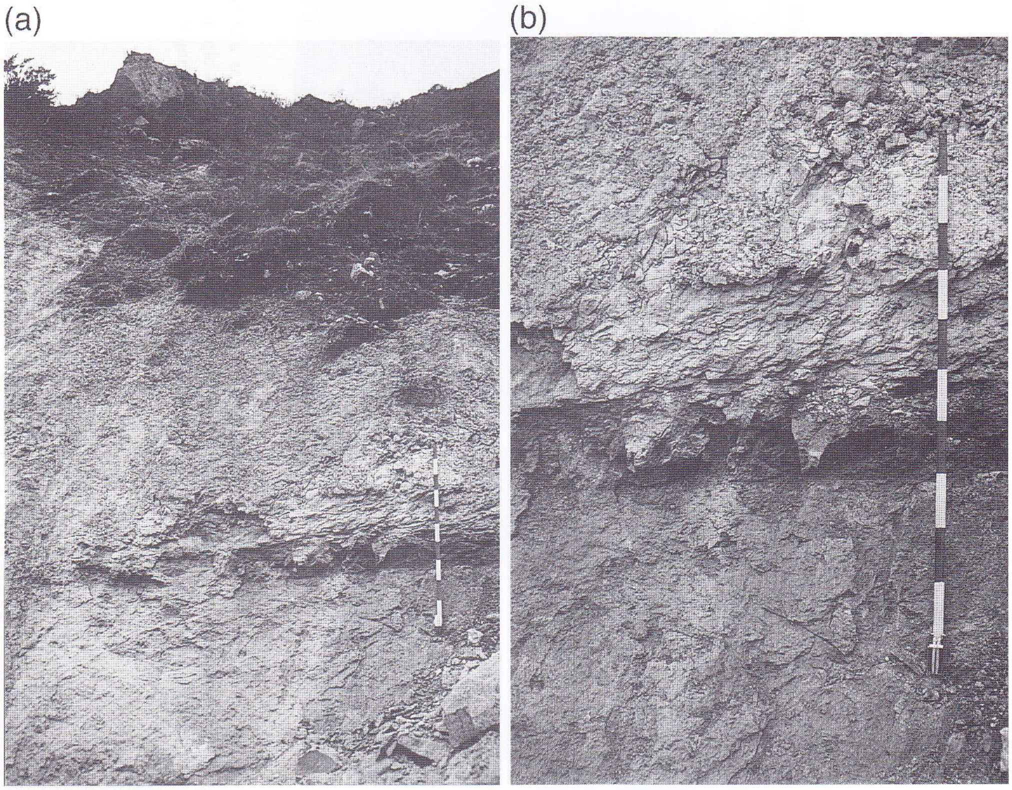

Fig. 3. (a,b) Horizon with schlieren of microbreccia and pumice-like hyalomylonite (maximum thickness 0.25 m) in high-brecciated migmatites and granites. (b) Shows detail from (a). Secondary sliding plane of lower Phushung II block. Location: W-side of Dranglung Chu valley, altitude 4130 m (see Fig. 1).

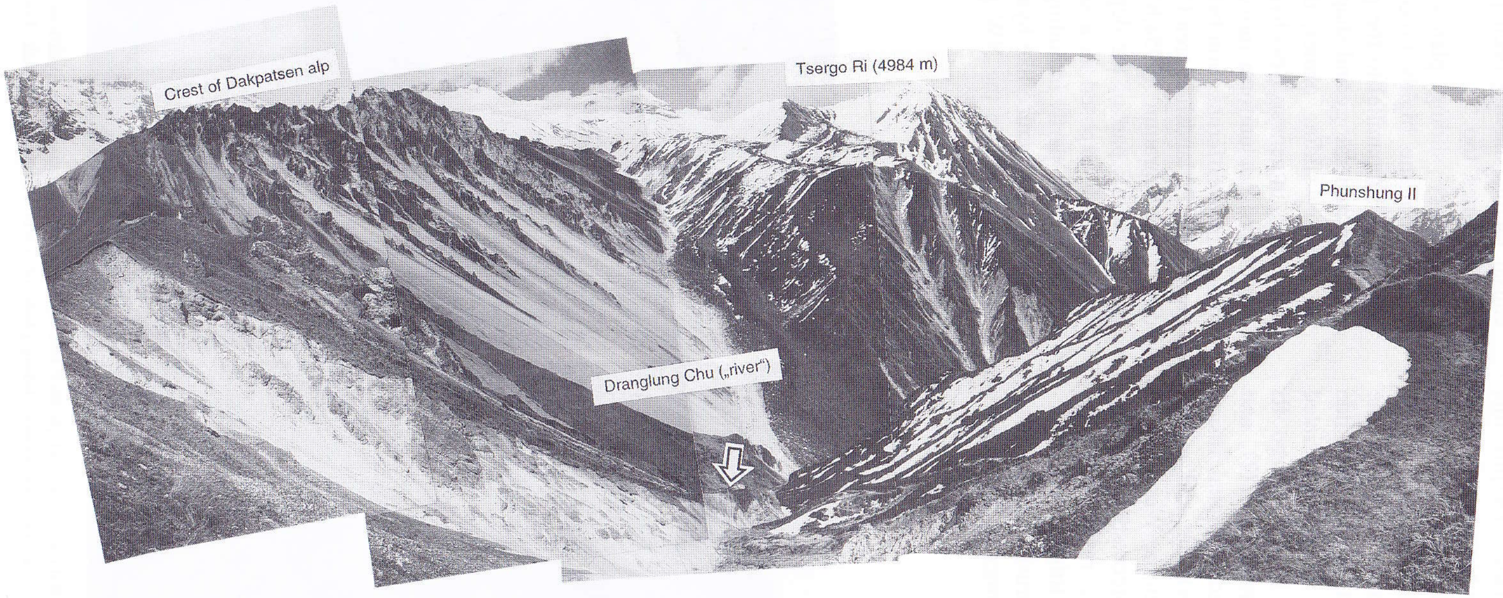

Fig. 4. Dranglung Chu valley, the landslide separating strike–slip fault system, outcropped as alternating cataclastic and pulverized rocks in the foreground and partly on the not-covered left side of the upper valley bottom. Background left: shattered crest of Dakpatsen alp. Background centre: Dranglung Chu ('river'), Tsergo Ri (4984 m). Foreground centre: site (arrow) with tertiary sliding planes (see Fig. 5a,b). Standpoint: crest north of Phushung II, altitude 4500 m (see Fig. 1). Line of vision towards ENE, exactly along the fault in the opposite direction of the mass movement motion.

flank of Dranglung Chu valley), is a straight horizon with a diffuse mixture and schlieren of pumiceous hyalomylonite and microbreccias (Fig. 3a,b).

Tertiary sliding planes of Tsergo Ri landslide occur within the mass of the brecciated landslide, almost vertical to primary and secondary sliding planes. Impacting on an obstacle (former Pangshungtramo Peak), the tertiary sliding planes divided the mass of the landslide like a strike–slip system: today's heavily eroded upper part of Dranglung Chu valley (Fig. 4). Alternating cataclastic and pulverized rocks, containing horizons of microbreccias (Fig. 5a,b) with partial lenses of hyalomylonite, show the same mineralogical composition as primary and secondary sliding planes.

The quarternary sliding or movement plane is a special type of the Tsergo Ri landslide, too, affected as the above mentioned strike–slip system while impacting Pangshungtramo Peak. Quarternary sliding planes are not exposed directly. Field evidence exists for a rapidly formed upthrust, the 'dry valley fault', along a break between Phushung I—Kyimoshung and Phushung II—crest of Dakpatsen alp (Fig. 1), in the NW part of the deposit, as a late consequence of the movement. The well-developed and carved valley east of Kyangjin Kharka is recently waterless and might have cut highly brecciated and/or pulverized rocks. The occurrence of hyalomylonite is hypothesized.

Outcrops in the Dranglung Chu valley (altitude 4110 m) have shown compact basal sillimanite gneisses (foliation: N 80°W, 20°NE), partly interrupted by up to 0.8 m thin, heavily sheared horizons (W 70°E, 50°NW) with polished and striated slickensides without any preferred direction. These black shear horizons can be ore mineralized in the lower

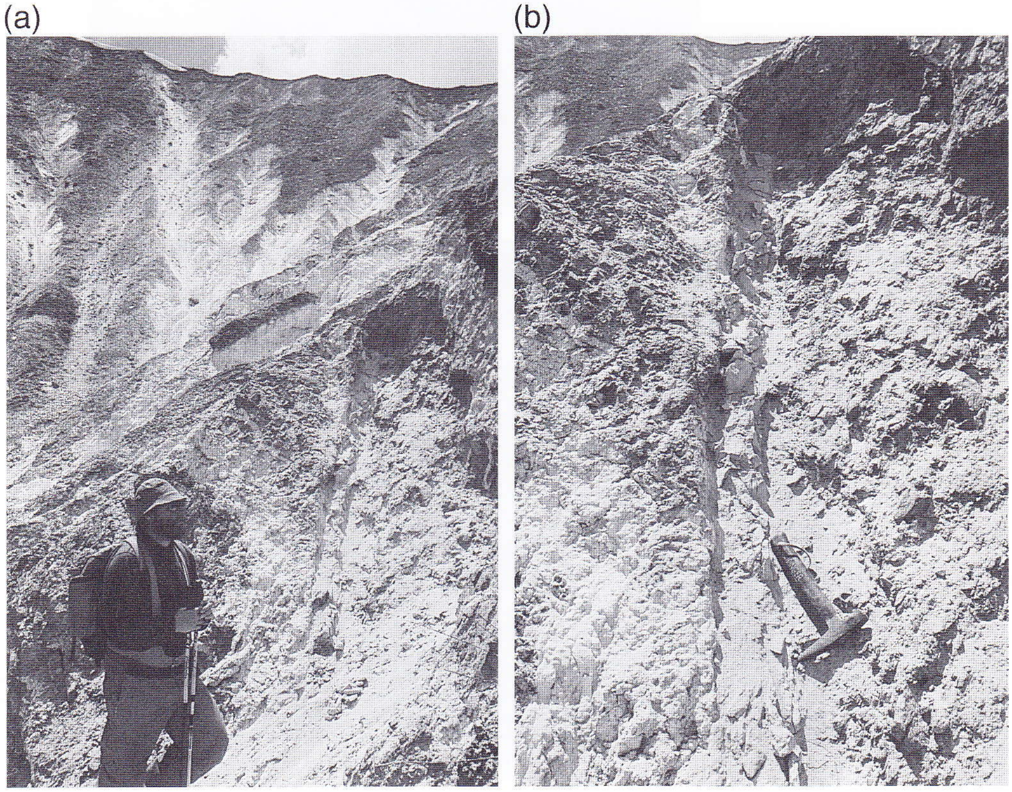

Fig. 5. (a,b) Outcropped vertical horizon (maximum thickness 0.1–0.15 m) of microbreccias (a) with lenses and schlieren of hyalomylonite within pulverized rocks [with detail, (b)] of the Dranglung Chu strike–slip fault. Location: gorge north of Phushung II, altitude 4445 m (see Figs. 1 and 4). Line of vision towards W, exactly in the striking direction of the horizon (N 90°W, 80°S) and the local movement direction of this landslide block towards W.

0.1–0.2 m. Similarity to sheared gneisses of the primary sliding plane (downwards outcropped) suggests that this horizon is a partly remobilized sliding surface, showing basement rock, affected by sliding-movement.

5. Position of types of sliding planes within the landslide deposit

Primary sliding planes: Scott and Drever (1953) described a frictional fused horizon in a narrow

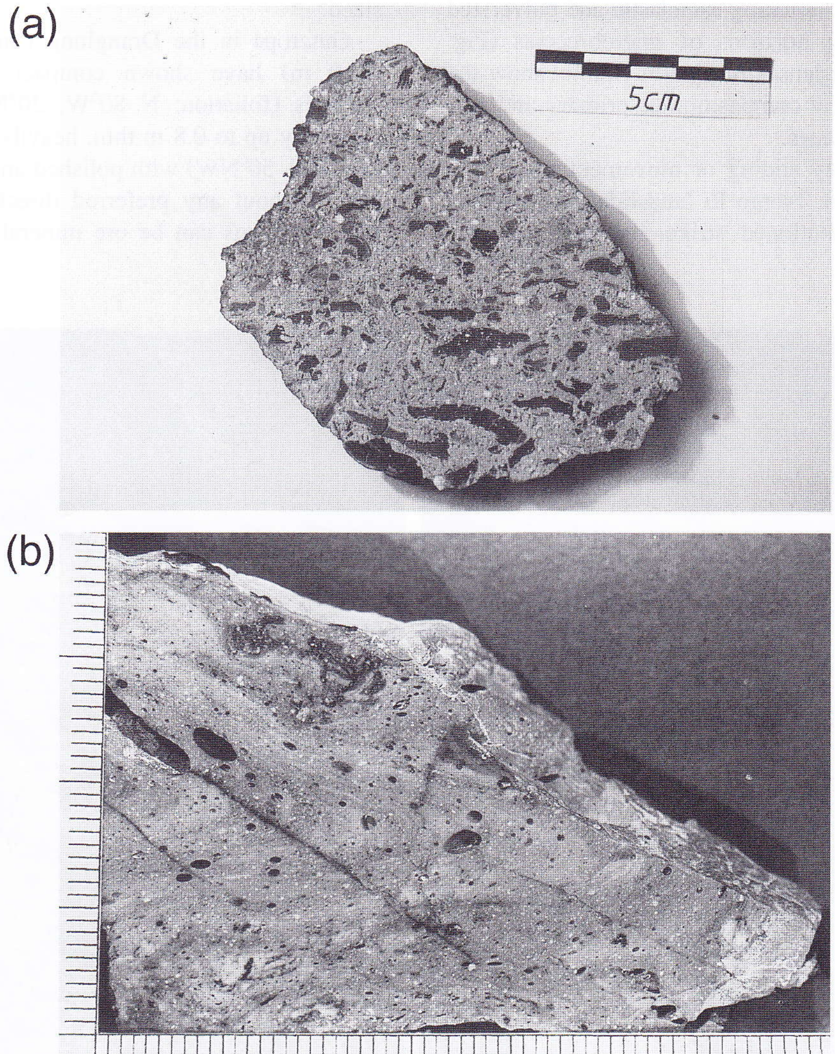

Fig. 6. (a,b) Hyalomylonites from primary sliding planes. (a) Sample of a 0.5-m thick horizon above biotite-rich gneisses, mixture of microbreccias and hyalomylonite (dark parts) without schlieren. Location: 150 m SW of Pana alp (1 km ESE Dzongdü), altitude 4010 m (see Fig. 1). (b) Sample of schlieren layer (thickness 0.02–0.08 m) above heavily sheared sillimanite gneiss, almost grey to white colour showing leucogranitic chemistry. Location: Dranglung Chu valley W-flank, foothill of Phushung II, altitude 4110 m (see Fig. 1).

erosion trench, northeast of Langtang 'airstrip' (SE Dzongdü, see Fig. 1). Masch and Preuss (1977) and Heuberger et al. (1984) later interpreted that horizon as the sliding plane of a giant landslide. Starting from this main outcrop, Weidinger (1992), Weidinger and Schramm (1995a,b) mapped further sites in the nearer proximity and all over the landslide deposit. This areal distribution offered evidence that physical conditions for the creation of hyalomylonite were sufficient at several places, although differences exist in formation, chemistry and texture (Fig. 6a,b) of the sliding plane. Exact measurements of the dip of the sliding plane outcrops in the center of the mass suggested the reconstruction of the main sliding direction towards WSW. According to elevation differences of the outcrops and geohydrological investigations of the landslide body in its entirety, an uneven basal sliding surface is hypothesized (Weidinger et al., 1995a,b; Schramm and Weidinger, 1996). Data from the SW ridge of the Pijung glacial cirque confirm the interrelationship between the irregular crest of Tsergo Ri landslide, the discordant leucogranitic intrusions with ore, the lithotectonic fault planes, and the neotectonic structures (Fig. 7). A neotectonic structure as a horizon 80 m thick (altitude 4850–4930 m) in this area is coincident with leucogranitic intrusions.

Secondary sliding planes: While mapping different types of rock qualities, mainly density of joint patterns, Weidinger (1992) and Weidinger and Schramm (1995a,b) noticed internal sliding planes. A blocky NW part and a gradationally brecciated SE part separate the mass of the landslide. The Tsergo Ri summit in the SE part shows separation from the lowest, highly brecciated hanging wall of the mass by a straight, secondary sliding plane parallel to the primary one. Up to four parallel horizons of microbreccias (0.5–0.7 m thin), partly including lenses of pumiceous hyalomylonite (Fig. 2a,b), could be detected from Tarche Pisa alp all along the S-flank of Tsergo Ri. 'Ponors' on the mountain ridge indicate weak rock strength (cataclasis and pulverization) and, therefore, indirectly indicating the slip plane. In comparison to this, the foot wall of Phushung II at the lower W flank of Dranglung Chu valley, exposes at 4110 m altitude another secondary plane close to the primary one. This horizon (0.3–0.4 m thin) consists of a schlieren mixture between pumiceous hyalomylonite and microbreccias (Fig. 3a,b) showing gangues into the lower parts.

Tertiary sliding planes: The Dranglung Chu valley strikes ENE–WSW in its upper part and separates the landslide. The valley changes the direction into almost N–S at 4240 m altitude, when reaching

Fig. 7. Partial view of the broken crest (scarp) of Tsergo Ri landslide, SW-ridge of Pijung glacial cirque. The primary sliding plane leads into a neotectonic structure that is associated with discordant leucogranitic intrusions (dotted line, arrow) below Yala Peak II which resisted the slope failure. Standpoint: S-flank of Yala Peak I, altitude 5240 m (see Fig. 1). Line of vision towards SSW.

and rounding the ancient, nearly compact sliding block of Phushung II, before changing again further down to NE–SW. Whereas this small mountain remained resistant against erosion because of greater rock strength, the prolongation of the valley gorge (exposed in the erosion trench between Phushung II and the crest of Dakpatsen alp with outstanding morphological activity) shows the highest brecciation with weak rock strength (Weidinger and Schramm, 1995a,b). Frequently changing cataclastic and pulverized migmatites and granites outcrop in this erosion trench—the hypothesized 'Dranglung Chu valley strike–slip fault system' (Fig. 4).

At 4445 m altitude, nearly vertical E–W striking horizons of microbreccias, similar to those of primary sliding surfaces, are exposed in pulverized rocks, giving evidence for this specific landslide that cuts a fault. One of these horizons (Fig. 5a,b), with a structural attitude of N 90°W, 80°S, is 0.1–0.15 m thin, and can be followed 5 m along strike. The microbreccia shows partial lenses and schlieren of hyalomylonite whose orientation outlined the general sense of the motion of the landslide from E to W.

6. Origin and generation of sliding planes and interpretation

Primary sliding planes: Preexisting lithotectonic and ore structures partly assisted as factors for rock failure by increasing the mountain collapse to a large scale (Weidinger et al., 1995a,b, 1996). These planes might have been used as sliding planes, mainly along the broken crest, with an unknown length in the sliding direction during an initial stage of the event. A similar function might have had preexisting metamorphites with deformational fabrics such as (ultra-)mylonites and pseudotachylites at an initial stage and partly during the last stage of the event, when velocity and friction were not sufficient to create hyalomylonites along newly formed planes. Hyalomylonite or 'frictionite' was created during the main sliding event according to the conditions of frictional heat (Erismann et al., 1977). Depending on the distribution of pre-existing lithotectonic structures, the paleorelief of the sliding base and the different velocity of some parts of the sliding mass, the deformational products, i.e., (ultra-)mylonites, pseudotachylites and hyalomylonites, assisted in the creation of an irregular surface of rupture, with slight variations in the altitude of the main primary sliding plane.

Secondary sliding planes: These internal planes were created approximately parallel to the primary ones during evasive movements. When the sliding mass was abruptly stopped temporarily because of unevenness and small irregularities (barriers) in the basement, the sliding mass was separated into several laterally terminated sheets parallel or subparallel to the main sliding surface. The local distribution of these planes within the landslide deposit is irregular and depends on lithologic conditions and specific position (how far a part has been moved during the event). The composition of hyalomylonite within microbreccias along these planes depends on the temporary speed or frictional heat to create hyalomylonite of the mass during its formation, and the time interval that such a plane was active until a barrier was overridden and movement was going on at the bottom of the mass.

Tertiary sliding planes: Vertical laminar stripes within the landslide deposits were noticed at many sites (Preuss, 1986; Abele, 1974, 1994). At Tsergo Ri landslide, preexisting neotectonic structures and resulting directions of mass movement towards WSW resulted in Pangshungtramo Peak, located SW of the recent landslide deposit, acting as a barrier. This obstacle forced the sliding mass to divide along a major strike–slip fault in today's Dranglung Chu valley into a less-moved NW part that stopped abruptly, and an onmoving SE part. Whereas the fault along Dranglung Chu valley is mostly eroded and shows high morphodynamics at both flanks (Ibetsberger, 1995), the uneroded outcrops of the prolongated valley, i.e., the flank between Phushung II and the crest of Dakpatsen alp, show almost vertical microbreccia horizons striking E–W within a highly brecciated (cataclastic and pulverized after Weidinger and Schramm (1995a,b)) lithologic matrix. Further vertical systems of sliding planes cutting the landslide deposits are hypothesized, but are still covered by Holocene sediments or have been removed by erosion.

Quarternary sliding planes: These planes of internal movement can neither be counted as those parallel to the primary ones nor to those vertical to the primary ones. These sliding planes are the result of local events, i.e., evasive movements in stopping blocky NW part in a last phase of collision with Pangshungtramo Peak (Weidinger, 1992).

7. Recent morphology as a result of tectonics, orientation of sliding planes, and form of the ancient landslide deposit

The generally high rates of morphological activities in the Tsergo Ri landslide-study area depend on the following.

Intensity of extreme relief (Fig. 1): From the highest seasonal settlement Kyangjin Kharka, on the floor of the upper Langtang valley (3920 m), up to the parent lodge of the landslide (Dragpoche and other unnamed peaks up to 6562 m), a relative difference in altitude of 2600 m is obvious. The horizontal distance amounts to 6 km. This intensity of extreme relief causes very steep slopes, locally $> 60°$.

Tectonic instability: Harrison et al. (1992, 1993) document a rapid uplift and unroofing of southern Tibet, beginning about 20 million years ago with rates of > 2 mm/yr. The Langtang valley runs parallel to the High Himalayan chains. With a mean exhumation in the order of 2 mm/yr, Hejl et al. (1997) reported from the Langtang area distinctly lower erosion rates than the high rates up to 8 mm/yr from the Nanga Parbat region (Zeitler et al., 1993; Chamberlain et al., 1995). Such mean exhumation rates are not the immediate expression of regular annual denudation but are mainly due to episodic erosion events, e.g., landslides and heavy floods.

Specific lithologic conditions: The area is located at the hanging wall of the High Himalayan Gneiss Zone, the Langtang Migmatite Zone, built up of Precambrian metasediments (e.g., series of migmatites and leucogranites, biotite–feldspar gneisses, augen gneisses, biotite–sillimanite gneisses and biotite–garnet–tourmaline gneisses), north of the MCT (Inger and Harris, 1992; Reddy et al., 1992; Massey et al., 1994).

Periglacial processes: The belt, where periglacial processes occur, spreads between the timberline and the glacier equilibrium line (5200 m). Presently, periglacial landforms, such as earth hummocks, solifluction lobes, turf-banked terraces, sorted polygons, talus slopes and striated ground, occur, as well as inactive landforms such as block streams and protalus ramparts (Watanabe et al., 1989).

Monsoonal precipitation regime: The climatologic data from Kyangjin Kharka (3920 m) show typical conditions of an inner High Himalayan valley. The west-facing valley is mainly influenced by the summer monsoonal precipitation, which constitutes 75% of the total precipitation. The average amount of precipitation per year, measured from 1988 to 1992, was 631.1 mm, while the average temperature was 1.86°C (Ibetsberger, 1995).

The evolution of the vegetation in this area (Miehe, 1990) is extremely dependent on the granulometric composition of the sediment and the amount of precipitation. Because of favourable preconditions (fine-grained sediment and high amount of precipitation), the whole study area up to the equilibrium line (5200 m) is nearly completely covered with grassland with variable shrubs, herbs, mosses and lichen, except the very steep slopes which have permanently morphological activity (e.g., Dranglung Chu valley).

Anthropogenic and zoogenic activities: The overgrazing of the alp pastures and the increasing activities of the trekking tourism in the Langtang National Park result in an anthropogenic/zoogenic degradation of the vegetative blanket. This evident development causes linear erosion and areal degradation.

The interrelationship of all these variables controls the morphological activity in the landslide area. The quantity and quality of the presently occurring geomorphic processes are controlled by the extreme shattering of the rocks that happened during the mass displacement.

Different 'hazardous' geomorphic landforms stand in close relation to the implication of the landslide event. Most of these forms are absolutely typical for the Tsergo Ri landslide area and less common in the area surrounding the landslide. The forms include the following.

- Rills, channels, gullies and areal degradation occur commonly as linear, erosive and denudational features all over the Tsergo Ri landslide area, but are very typically developed at the Tsergo Ri and the Dranglung Chu valley slopes.
- An outstanding area with an extremely high density of linear erosional features occurs on the S-

and SW-facing slopes below the Tsergo Ri plateau. These channels and gullies are all situated at the granitic upper hanging wall of the landslide deposits. During the mass displacement, an extreme shattering of the leucogranites occurred. The brittle-breaking granites are much more susceptible to erosion than the gneisses and migmatites, which build up the faces of the footwall. These upper slopes can be characterised by many parallel-running, deep-eroded gullies. These linear erosive features begin at the sharp edge of the Tsergo Ri plateau, where small catchment areas of the individual gullies were divided by isolated rocky ridges. After a few hundred meters, these deeply eroded gullies grow together and turn into an extensive denudation area. This area is located at the lithological transition zone to the lower hanging wall, which is composed of gneisses. This morphologically flattens the slope at this transition zone. Only some erosional gullies run on through the lower hanging wall and the gneissic bedrock to reach the Langtang valley bottom (e.g., gully above the 'airstrip' where the sliding surface is exposed). The gneissic bedrock outcrops in the face which has high resistance to linear erosion. Small waterfalls between Dzongdü and Nubamathang (Fig. 1) are characteristic for the whole basement, south wall of the Tsergo Ri massif.

• Another area with an extremely high density of linear erosive features is the Dranglung Chu valley in the landslide deposits, which runs into the main Langtang valley between Kyangjin Kharka and the Langtang 'airstrip'. The SE-facing Dranglung Chu valley slopes below the Dakpatsen crest show an extremely high morphological activity. The crest, with an elongation of nearly 2 km, is extremely rugged and furrowed, which was primarily produced during the displacement of the Tsergo Ri mass. The lithological composition of the leucogranites is similar to the situation of the upper Tsergo Ri slopes in that the leucogranites are very susceptible to erosional and denudational processes. The upper division of these slopes is characterised by isolated rocky ridges that border the small debris catchment areas of the erosional gullies. From these, niches debris cones, more than 500 m in length, extend down to the bottom of the Dranglung Chu valley. The gullies of this area are wider, but with less water run-off as compared to those in the Tsergo Ri area. These slopes show permanent morphological activity, linear erosion together with areal degradation.

• An uncommon morphological activity at the western edge, but outside the Tsergo Ri landslide area, shows a steep slope east of Pangshungtramo Peak. An erosional channel was cut deep into the hard rock, with a fresh debris cone at the foot. This linear erosive feature follows a pre-existing neotectonic structure which can be connected with mass displacement. According to the gliding direction of the landslide mass (ENE/WSW), the E-facing slopes of Pangshungtramo Peak were severely affected as the landslide-barrier zone. The shattering of the gneissic bedrock, which occurred during the mass collision, is responsible for the persistently morphological activity.

Apart from the big 'badland-areas' of the Tsergo Ri S- and SW-facing slopes, and the SE-facing Dranglung Chu valley slopes, many smaller mass movements, up to 100 m^3 occur along with material-accumulation areas. Slides, cracks and accumulation of material include the following.

• Stepped slopes formed by yak grazing are very typical for the area of the Tsergo Ri landslide. Two different processes are responsible for soil mobilization. Either increased water infiltration, or the action of needle-ice, together with wind deflation and wash working on the bare treads formed by yaks, are responsible for the soil erosion and the collapse of the vegetation cover (Watanabe, 1994). This geomorphic phenomenon was studied in the small valley NE of Kyangjin Kharka, at an altitude of 4300 m. The average dip of the slopes at this area amounts to 35°–40°. Besides an exact documentation of the erosional cracks in the field, older photographs were used for comparison (Schneider, 1970; Heuberger, 1978; Schneider, 1983; Ibetsberger, 1991; all unpublished). Between 1970 and 1991, the existing erosional cracks have not expanded. The photography of Schneider (1970), however, shows a lot of small erosional cracks all over the valley which were morphologically active. Photographs by Ibetsberger (1991), made more than 20 years later, show erosional cracks in shape and size which were nearly similar to the former ones. The top of the erosional cracks, resulting from frost action or cliff-sapping, show no changes of expansion of any kind. On the other side, it was detectable; removed soil blocks received an evident stabilising input and took roots in the floor. These islands of vegetation have grown together and have recovered big parts of the erosional cracks with vegetation. This matter of fact can be transferred to most other erosional cracks at the Tsergo Ri landslide area, which indicates a slow improvement of the situation of soil erosion in this area. Watanabe (1994) corroborates these statement when he noticed that between 1988 and 1990, no new soil erosion scars of any kind were detectable.

• The valley of the Dranglung Chu, which cuts through the Tsergo Ri landslide deposits, runs into the main valley of the Langtang Khola, E of Kyangjin Kharka, and forms a giant alluvial fan. To study the development and changes of the fan complex between 1970 and 1995, photographs were analysed (Schneider, 1970; Heuberger, 1978; Schneider, 1983; Ibetsberger, 1991; Ibetsberger, 1995). The result of these analyses was nearly similar to that of the erosional cracks in the small valley, NE of Kyangjin Kharka. With the exception of a catastrophic debris flow which occurred between 1970 and 1978 and damaged the alp settlement of Dzongdü (Ibetsberger and Madhikarmi, 1995), no similar events have been recognised up to now. The long-term development of the fan complex shows stabilising by resettlement with vegetation. Morphological activity is presently decreasing.

In some parts of the Tsergo Ri landslide area, a decrease in the recent amount of morphological activity is obvious. First, the whole ecosystem of the landslide area is conditionally unstable. This positive development, with an evident regression of morphological activity, can change easily and quickly. Second, common conclusions of possible climatic changes are not realistic. The ancient landslide deposit is mostly eroded by the last high-, late-, post-glaciation and subsequent processes. Orogenetic tectonics, neotectonics, movements along primary basal and secondary, tertiary and quarternary internal sliding planes, and the extension of the former deposit have utilized the preexisting structures as pathways to create the special shape and morphology within the recent landslide area.

The outcrop of the generally WSW-dipping primary sliding surface along the southern slopes of Tsergo Ri mountain has been subjected to widespread erosion due to weathering and glaciation of the brecciated hanging wall that exposed the detritus-covered gneissic basement over a wide range. The erosional form of a triangular area between the alps of Dzongdü, Pana, Dygiapsa and Tashigang (from W to E, see Fig. 1) is only interrupted by three uneroded tiny laps of landslide material around Pana, which bears the most famous hyalomylonitic horizon. The neck of the landslide deposit, in the forefield of the Yala Tsang and along the valley of the same name, as well as the broken crest, were partly affected by paleo- and recent glaciation.

Whereas the secondary sliding plane in the Dranglung Chu valley did not produce any special morphological features, the sliding plane dividing the top of Tsergo Ri from the more disturbed base is morphologically well-developed. That erosion edge was partly used by the Langtang glacier during the last high glaciation (Ibetsberger, 1993), forming the obvious 'steps' in the Tsergo Ri southflank of Tarche Pisa and north of Pana alps.

The most interesting and spectacular morphological break within the landslide deposit was created by the vertical tertiary sliding plane(s) or strike–slip system. The morphologically highly active Dranglung Chu valley resulted from the collision against Pangshungtramo and the division of the mass into two different parts. Subsequent erosional processes and subsurface flowing waters could easily wash-out and deepen the valley. Besides the valley formation, the 'dry valley fault', a quarternary movement plane, was built as an upthrust when the NW-part of the mass was stopped. The collision itself destroyed the ancient Pangshungtramo Peak and forced the Ledrub–Lirung Tsang to deviate from a NW–SE to a N–S direction and changed herewith again the recent morphological shape. The Pangshungtramo Peak is an uncommon example of partial erosion along structures outside the landslide deposit.

8. Conclusion

Analyses of regional tectonic features and the internal composition of Tsergo Ri landslide in comparison with the morphodynamic evolution of the upper Langtang valley reveal significant interrelationships between predesigned orogenic fabrics, landslide-triggered structures and the recent shape of the extensively eroded landslide deposit. The current shape of Tsergo Ri and its surroundings resulted from the initial landslide event followed by complex and different morphological processes along: (i) preexisting lithotectonic and neotectonic structures, (ii) basal and internal sliding planes, triggered by landslide dynamics, (iii) highly brecciated (cataclastic and pulverized) parts of the landslide deposit, and (iv) ancient preexisting glacial valleys and troughs which partly had to change direction.

This observation is supported by recent morphodynamic active parts of the deposit (Dranglung Chu valley and related fan east of the Langtang 'airstrip'). The prehistoric landslide area of Tsergo Ri is an outstanding scientific site but also is a hazardous part of the High Himalayan Terrain with potentially serious implication for human occupants in future.

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