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On preparatory causal factors, initiating the prehistoric Tsergo Ri landslide (Langthang Himal, Nepal) [1]

Johannes Thomas Weidinger [a,*], Josef-Michael Schramm [a], Rouben Surenian [b]

[a] *Institut für Geologie und Paläontologie, Universität Salzburg, Hellbrunnerstraße 34, A-5020 Salzburg, Austria*
[b] *Geologische Bundesanstalt Wien, Rasumofskygasse 23, A-1031 Wien, Austria*

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Abstract

The most probable series of causal factors and their complexity make analysis and synthesis of the Tsergo Ri landslide (Langthang Himal, central-north Nepal) restricted, especially in this case of a prehistoric event with a spread of age data. Interpreting morphologic, lithologic, structural and engineering-geologic aspects in relation to preparatory causal factors and subsequent processes will therefore be only an approach.

The solid basement and the broken crest of the landslide, as well as the surrounding areas of the upper section of Langthang valley, are to be included in the High Himalayan Crystalline: leucogranitic dikes (dipping towards the southwest) intruded gneisses and migmatites (primary foliation towards the northeast). Formation of these dikes caused one of many factors or preexisting structures, leading to the development of the landslide. In addition, subsequent tectonic movements and related seismicity forced specific deformation of metamorphic rocks: ultramylonites, two generations of faults with striated slickensides, and pseudotachylites degraded to substantial horizons of weakness. The spatial orientation enabled predetermination of subsequent morphologic processes (e.g., slope destabilising forces, trend and dip of sliding).

In association with leucogranitic intrusions, a disseminated mineralized, extensive sulphidic ore structure outcrops at the broken crest of the landslide. Due to brittle rheologic behaviour and poor weathering resistance this ore-bearing horizon (parallel to the main sliding plane) also made the slopes susceptible to sliding. Material displaced from the scarp by landsliding, was mixed up with rocks from undisturbed ground and subsequently cemented by secondary ore mineralization, thus forming ore-breccias at the top of the surface of rupture.

Neotectonic structures, caused by stress release associated with erosional processes and similarly oriented as the existing zones of weakness, may have acted as a preparatory and/or triggering causal factor for slope destabilisation too.

Hyalomylonite from primary and secondary sliding surfaces, as well as gneiss from the solid basement of the landslide, analysed by means of scanning electron microscopy and energy-dispersive X-ray analysis, indicate deformational patterns attributed to tectonics and landslide mechanisms. The deformation feature is distinguished clearly from those created by shock-wave events (i.e. impact-triggered Köfels landslide, Tyrolean Alps, Austria). Thus, seismic activity might have been the triggering causal factor for the Tsergo Ri landslide event.

* Corresponding author. Fax: +43 662 8044-621.

[1] Dedicated to professor Dr. Helmuth Heuberger

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1. Introduction

The outstanding morphologic and tectonic position, giant scale, and especially the frictional fusion at the surface of rupture, emphasize the Tsergo Ri landslide (Langthang Himal, central-north Nepal) as an exemplary site with cumulative basic information. Scott and Drever (1953) described frictional fusion (hyalomylonites) in the Langthang valley as being associated with a thrust, presumably the Main Central Thrust (MCT). Based on petrological and geomorphological evidence, Masch and Preuss (1977), Masch et al. (1981) and Heuberger et al. (1984) recognized this area as a giant mass movement with rock fusion at the sliding surface (fission track age 'some' 10^4 years, Wagner, 1995). With a displaced mass of about 10^{10} m^3, the Tsergo Ri landslide ranks as one of the largest terrestrial mass movement events.

Field and laboratory work from the engineering-geologic and geomorphologic view (Weidinger, 1992; Ibetsberger, 1993) supplied the principles. An engineering-geologic map, providing basic information of the lithological, structural, hydrological and morphological features, enabled the reconstruction of different phases of displacement, deposition and erosion (Weidinger and Schramm, 1995a,b; Ibetsberger, 1995, 1996). In addition, analyses of preexisting structures within the solid basement of the landslide area pointed to new conditions conducive to landsliding. The broken crest of the Tsergo Ri landslide is situated at an extraordinary lithotectonic position: leucogranitic intrusions within gneisses and migmatites, ultramylonitic and pseu-

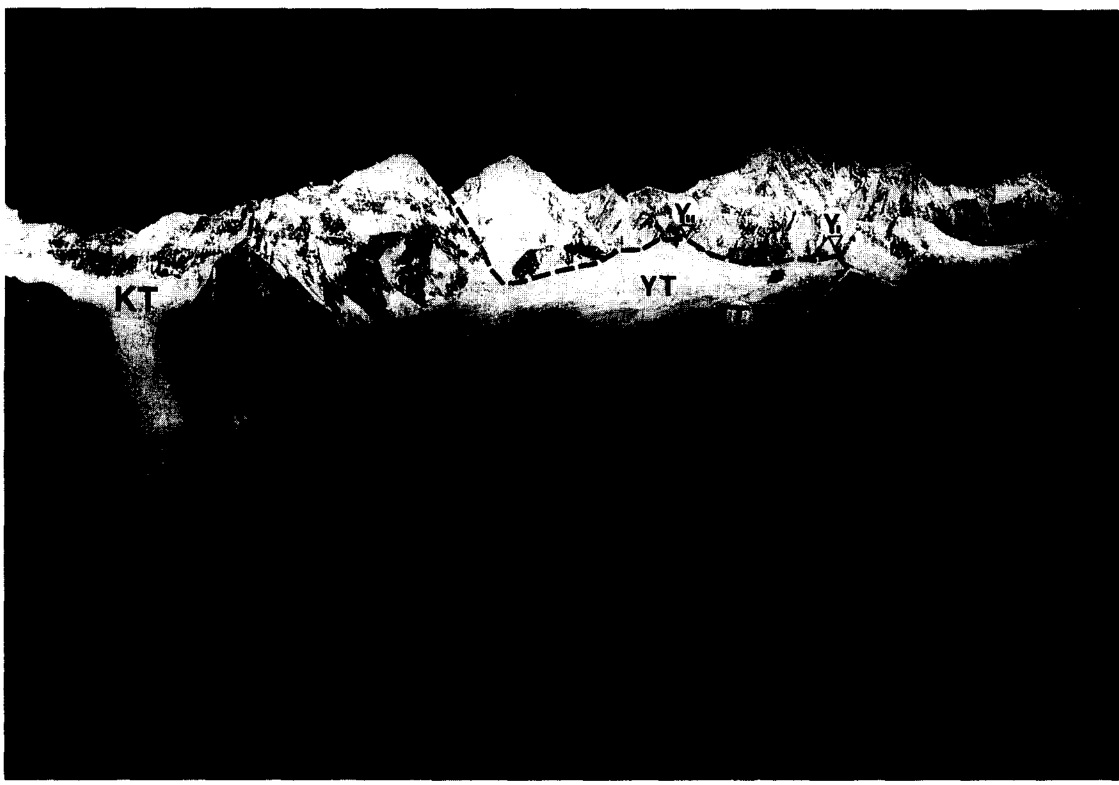

Fig. 1. Photograph of the Tsergo Ri landslide area. Dashed lines indicate scarp, broken crest (left side and centre) and outcropping sliding surface along neotectonic structures in the Langthang valley (lower right side). Dash-dotted line indicate supposed former prolongation of scarp towards the southeast, subsequently eroded. Dragpoche, 6562 m (*D*); Dranglung valley (*DV*); Gyaltsan Gompa, 3920 m (*G*); Kyimoshung Tsang (*KT*); Kyimoshung Peak, 4640 m (*K*); Langthang valley (*LV*); Phrul Rangtshan Ri, 6940 m (*P*); Phushung Peak, 4360 m (*PH*); glacial cirque of the Pijung alp (*PA*), Shisha Pangma, Gosainthan, 8027 m (*S*); Tsergo Ri, 4984 m (*T*); Yala Peak I, 5520 m (*YI*); Yala Peak II, 5749 m (*YII*); Yala Tsang (*YT*). Location: Naya Kanga glacier at 5720 m altitude, 1.5 km WNW of Gangtsa La pass (5122 m), line of vision towards the northeast.

dotachylitic horizons, slickensides, and an extensive disseminated mineralization of sulphidic ore structures associated with leucogranites formed a surface of weakness. This horizon together with neotectonic release joints, shifted the slopes into a marginally stable state. Scanning electron microscopy (SEM) and energy-dispersive X-ray analyses (EDX) on hyalomylonite, pumice and gneissic basement confirmed tectono-mechanical landslide-caused dynamics and suggested seismic activity as the triggering causal factor for this event.

2. Regional geologic setting

The Tsergo Ri landslide area is situated in the upper section of the Langthang valley, about 60 km north of Kathmandu (Fig. 1). It is located north of the MCT at the hanging wall of the High Himalayan Gneiss Zone (=Langthang Migmatite Zone: Kyangjin and Langshisa Unit, Reddy et al., 1992) or Greater Himalayan Sequence (Macfarlane et al., 1992; Macfarlane, 1993), consisting of Precambrian metasediments: gneisses, migmatites and intruded leucogranites. These series dip gently to the northeast (20–30°) and are separated by the South Tibetan Detachment System (STDS) from the series of the Tibetan Slab.

As the result of a polyphase metamorphic history, the Langthang metasediments show an inverse metamorphic isograde pattern. A first heating event of Barrovian regional metamorphism, prior to 34 million years, affected the base of the High Himalayan thrust sheet and activated the MCT. Upper parts of the thrust sheet were overprinted by a second heating event between 17 and 20 million years to sillimanite-grade due to heat focusing because of a different thermal lithological conductivity. This event caused anatexis and intrusion of crustally derived leucogranitic magmas (Inger and Harris, 1992).

3. Leucogranitic intrusions at the scarp of the Tsergo Ri landslide

According to Inger and Harris (1992) a substantial body of leucogranite intruded into Tethyan sediments, forming a 10^3 m thick network of sills and subconcordant sheets. In contrast, High Himalayan metasediments with subvertical leucogranitic feeder dikes (width 0.05–3 m) in the upper part, strike cross-cutting the primary foliation N 70°W and dip >60° SW. At the scarp of Tsergo Ri landslide (the SSE- and NE-wall of Yala Peaks I and II, SSE-wall of Dragpoche) two different generations of leucogranitic dikes occur: (1) one thin (cm–dm) and concordant (NE-dipping); (2) the other thick (dm–m), discordant (SW–W-dipping) to primary foliation and first generation of leucogranitic dikes, associated with parallel structures, affecting disintegration and corresponding to the primary sliding surface.

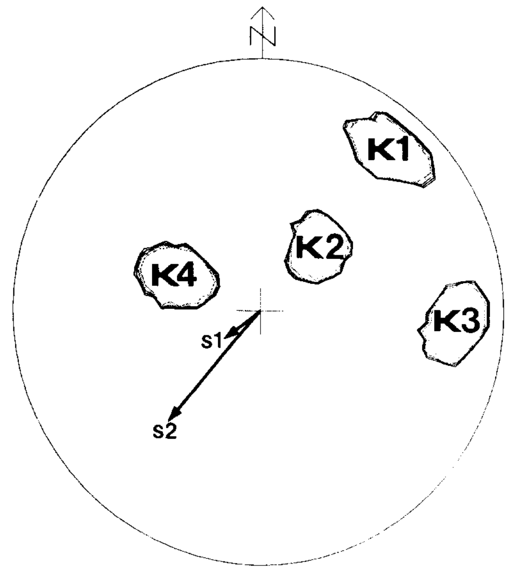

Fig. 2. Stereographic representation (lower hemisphere) of fabric data, surveyed at the S-wall of the Langshisa Ri W-peak (alt. 6145 m). 34 data points: active joints and related structures. Open mega-joints (*K1*); set of joints (*K2*) with identical orientation as intruded leucogranitic dikes; slickensides with striation (*S1*) related to K1; slickensides with striation (*S2*) related to *K2*; neotectonic release joints (*K3, K4*) providing rockfalls.

These dikes are followed to the hanging wall by huge intruded cylindric granitic bodies. Similar structural patterns in the granites have been surveyed in the upper section of the Langthang valley, assisting rockfalls and erosion (Fig. 2) at the NW-wall and S-wall of the Langshisa Ri W-peak, along the axis Pemthang Karpo Ri (6910 m)–Pemthang Ri (6758 m), in the S-wall of the Langthang Ri (7205 m), and also at the basement of the landslide area, in the steep walls north of Yathang, Mendang and Nubamathang. One of the structures, the boundary between footwall and hanging wall of the landslide area (Heuberger

Fig. 3. Broken crest or scarp of the Tsergo Ri landslide, SSE-wall of Yala Peak I (*Y*): discordant leucogranitic dike (*G2*), crossing clustered concordant dikes (*G1*). Dipping of G2 (N 08°W, 17° W) and ore structure (*OS*) (N 02°E, 20° W) identical with sliding direction. Striated faults (*fp*) in G2 dipping west. Ore joints (*Oj*) (N 45°E, 75° NW). Location: foothill of Yala Peak I, alt. 5180 m, line of vision towards the north.

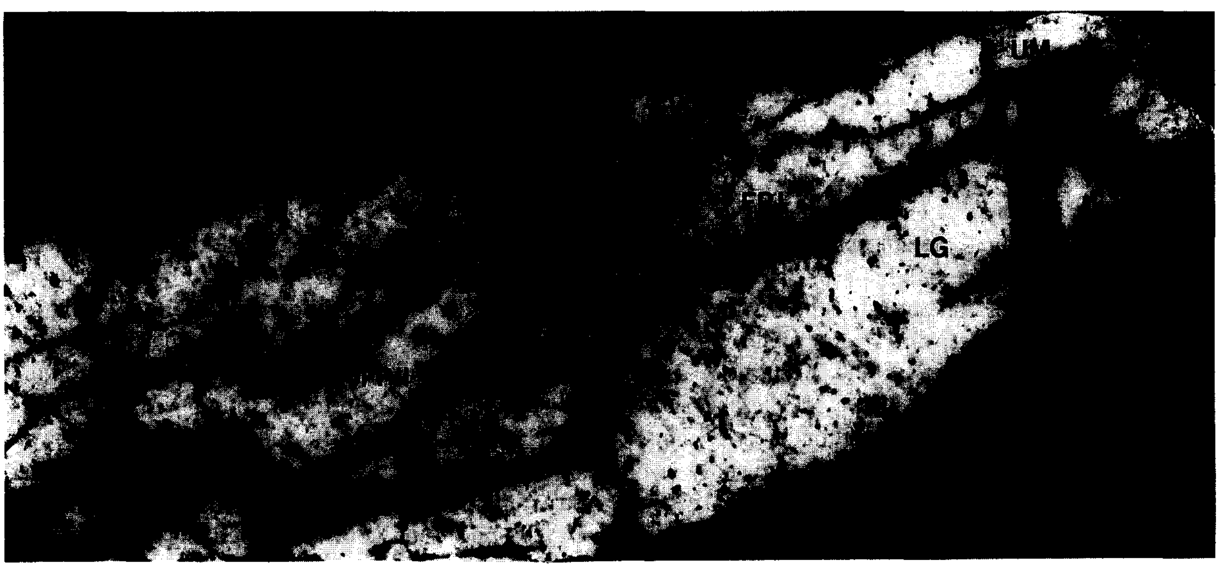

Fig. 4. Two generations of tectonic triggered fault planes and slickensides (*FP I, FP II*), filled with black, microcrystalline tourmaline (*schorl*) in discordant, leucogranitic dike (*LG*) near the broken crest of the landslide. These horizons dip parallel (flat and steep to the southwest) to primary sliding plane of the landslide (*md*). Documented translation of FP I by FP II between 5 and 10 mm (see upper central part of photograph). FP II partly curved running into the direction of FP I. FP I cut off by younger ultramylonites (*UM*) dipping extraordinarily steep to the northeast (see upper right corner). Location of sample: SSE-wall of Yala Peak I, alt. 5210 m.

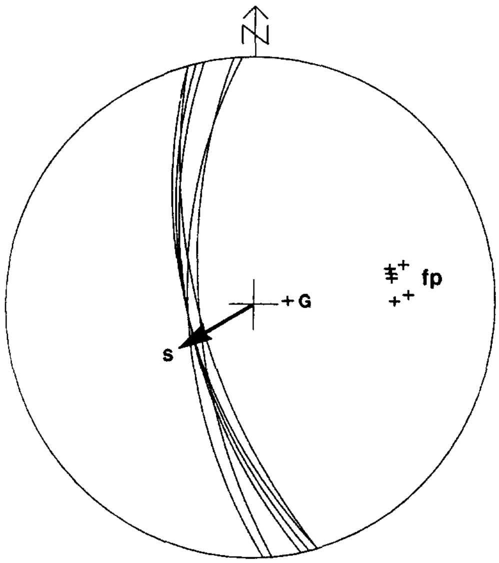

Fig. 5. Stereographic representation (lower hemisphere) of fabric data, surveyed at the SSE-wall of Yala Peak I (alt. 5465 m): discordant leucogranitic dike (*G*); cf. Fig. 3: G2 dip parallel to sliding plane of landslide, striated faults, slickensides (*fp*), and striation (*S*) related to *fp*.

et al., 1984; Weidinger and Schramm, 1995b), corresponds to sliding surfaces.

At the S-wall of Yala Peak I a discordant granitic dike, 5 m in width, and a related dike-swarm exactly mark the broken crest (Fig. 3). The dikes cross clustered veins of older, concordant granites with smaller thickness. The brittle hardrocks are brecciated. At the top of Yala Peak I there is evidence for small dislocation downwards due to stress along structures striking N 40°W and dipping 40° SW. The younger discordant granites are affected by two fault plane generations and one mylonitic generation, showing at least three different tectonic-triggered kinematic phases (Fig. 4). Flat (oldest) and steeply SW-dipping planes (both older than mylonites) assisted in the destabilisation of the SW-dipping dikes. Veins (1–2 mm in diameter) are mostly filled with black tourmaline. Tectonic striation (2–3 mm wide) occurs (Fig. 5); joint sets with slickensides are similarly oriented.

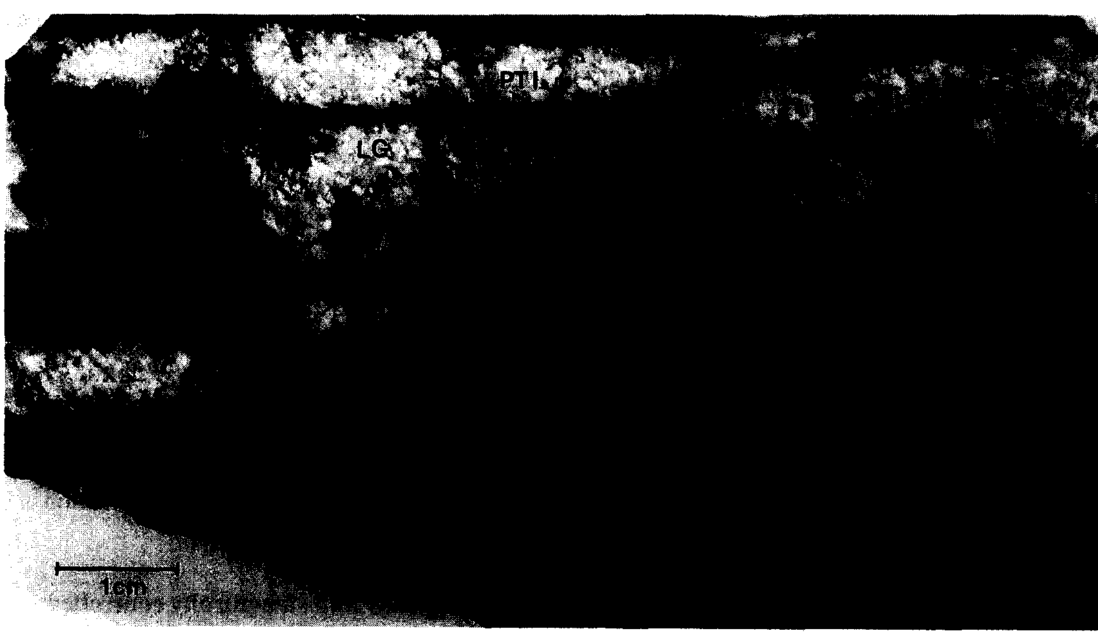

Fig. 6. Implosion textures of palaeoseismic-triggered pseudotachylites (*PT*, extension centimetres to max. decimetres) partly showing two main directions (*PT I*, *PT II*) within discordant fragmental and partly brecciated leucogranitic dike (*LG*), rich in schorl (*T*). Documented dislocation (delta s) of millimetres to max. centimetres (note cracked tourmaline crystal right of the centre). Both 'generations' of pseudotachylite dip parallel (gently and steep to the SW, to left side) to the movement direction (*md*) of the landslide. Location of sample: northeast ridge of the Pijung glacial cirque (supposed prolongation of broken crest towards the southeast), alt. 4200 m.

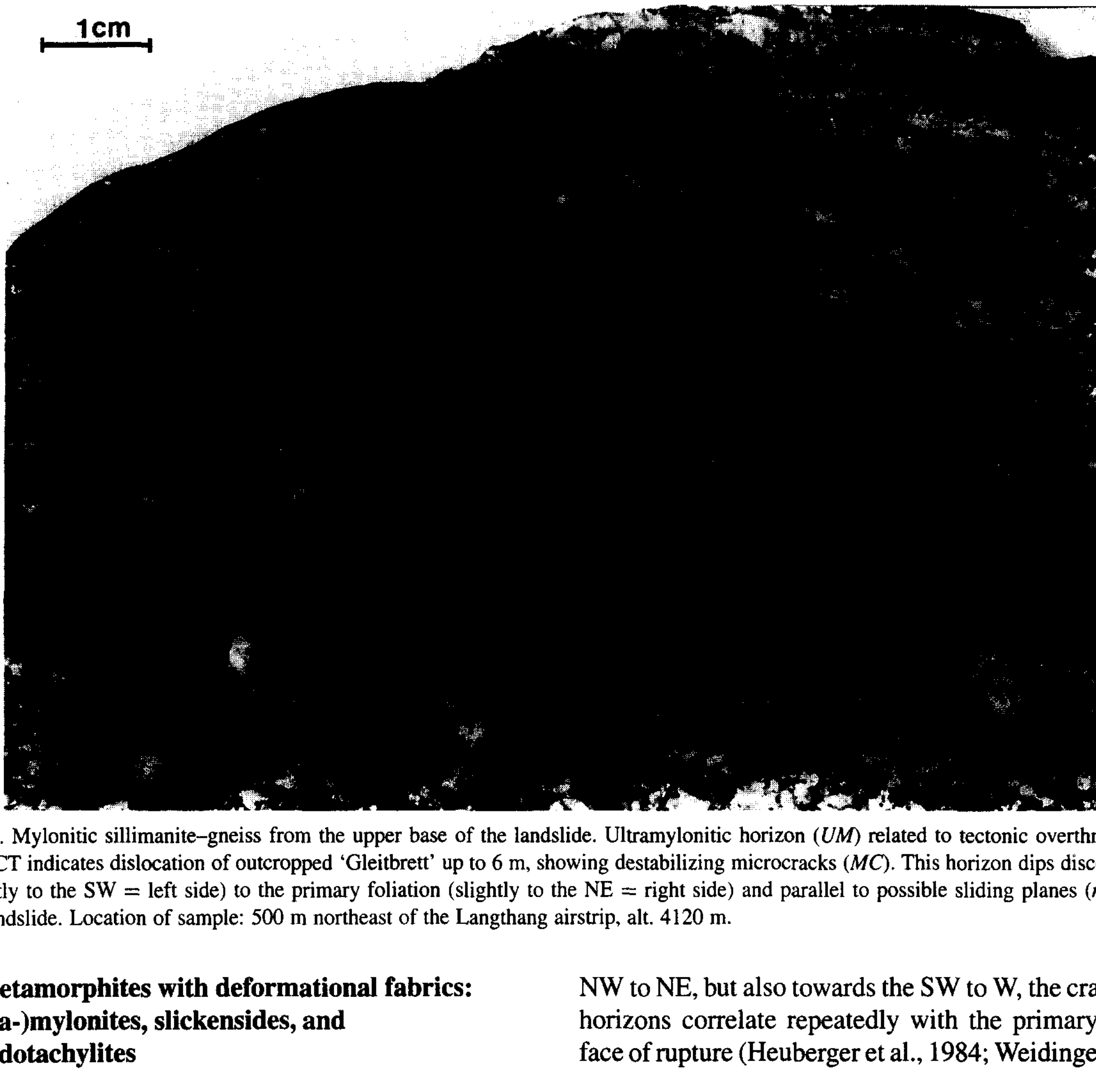

Fig. 7. Mylonitic sillimanite–gneiss from the upper base of the landslide. Ultramylonitic horizon (*UM*) related to tectonic overthrusting on MCT indicates dislocation of outcropped 'Gleitbrett' up to 6 m, showing destabilizing microcracks (*MC*). This horizon dips discordant (slightly to the SW = left side) to the primary foliation (slightly to the NE = right side) and parallel to possible sliding planes (*md*) of the landslide. Location of sample: 500 m northeast of the Langthang airstrip, alt. 4120 m.

4. Metamorphites with deformational fabrics: (ultra-)mylonites, slickensides, and pseudotachylites

In the upper section of the Langthang valley widespread occurrence of deformational fabrics such as (ultra-)mylonites, slickensides, and pseudotachylites in metamorphic rocks gives evidence for tectonic overthrusting and associated palaeoseismic events (Fig. 6) near the MCT and within the High Himalayan Gneiss Zone (Masch and Preuss, 1977). Macfarlane (1993) describes a dominating top-to-the-south sense of shear in the lower portion of the Greater Himalayan Sequence, and some (overprinting?) top-to-the-north kinematic indicators in the upper portion of the sequence. The STDS does not outcrop in the Langthang area. The brittle reaction on stresses of those hardrocks forces microcracks (Fig. 7), aggregating horizons of inhomogeneity. Dipping towards the NW to NE, but also towards the SW to W, the cracked horizons correlate repeatedly with the primary surface of rupture (Heuberger et al., 1984; Weidinger and Schramm, 1995a,b). At some points of the landslide (e.g., 200 m northeast of Dzongdü alp) a preexisting mylonitic horizon, reworked due to landslide activity, exactly indicates the boundary between the gneissic basement and the brecciated hanging wall (Fig. 8). The orientation of hyalomylonites (primary and secondary surfaces of rupture) and ultramylonites, as well as the location of sulphidic mineralization at the scarp are outlined in Fig. 9.

5. Lithologically and structurally controlled sulphidic mineralization of Yala Peak I, Yala Peak II, Dragpoche and adjacent areas

Gently (<20°) SW-dipping leucogranitic dikes near the broken crest are associated with a dis-

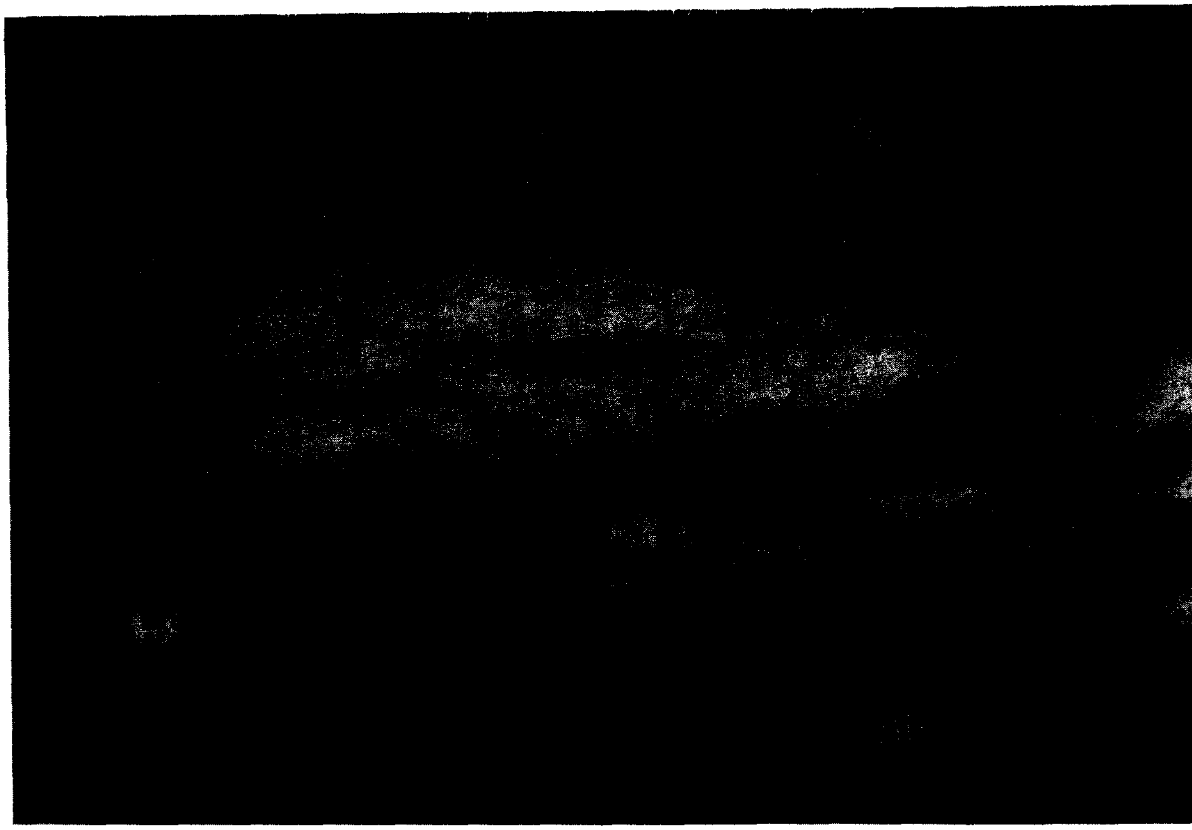

Fig. 8. Preexisting, tectonic triggered, and due to landslide-activity, reworked ultramylonitic horizon (*um*, dark layer) used as sliding plane (*SP*) of the landslide (arrow showing movement direction (*md*) towards the SW, top to left), dividing the base of sillimanite–gneiss (*gn*) from the hanging wall, partly occurring as schlieren and microbreccia (*mb*), and toe (*t*). Location: 200 m northeast of the Dzongdü alp, alt. 3960 m.

seminated mineralized ore structure (Fig. 10). This structure accompanies the broken crest of the Tsergo Ri landslide 3 km in the strike direction (NE-wall of Yala Peaks I and II), and 3 km along the dip (SSE-wall of Yala I and SSE-wall of the Dragpoche). Towards the NE the ore-bearing leucogranites disappear underneath the depression between the Dragpoche and Phrul Rangtshan Ri. The ~10 m thick ore body was formed as a straight, partly brecciated horizon (striking N 50°W, dipping 15° SW) with primary sulphide and secondary oxide mineralization (Weidinger et al., 1995).

In the SSE-wall of Yala Peak I, at 5465 m, the ore structure appears in the broken crest striking N 02°E, dipping 20° W. This corresponds remarkably with the surface of rupture of the landslide. While the ore horizon (thickness at this point 2.5–3 m) bears almost massive oxidized sulphides in the uppermost 0.3–0.4 m, the lower parts show dissemination with oriented veinlets (width 0.1–0.9 mm) and ore-filled microcracks (Fig. 11), corresponding again with the direction of movement of the landslide towards the SW (Fig. 12). The whole mineralized horizon is highly porous (high permeability relating to groundwater) and brittle breaking. It consists of xenomorphic pyrrhotite with irregular contours and inclusions of pyrite, chalkopyrite, zonar sphalerite, galena, and arsenopyrite. Interfaces as well as net-like cracks in pyrrhotite are transformed into marcasite with a cryptocrystalline matrix of marcasite and pyrite showing typically 'birdseyes'. The alteration of pyrrhotite as well as skeletal growth of pyrite also assisted in destabilizing the bedrock. At 5260 m altitude in the same area brownish weathered joints with varying strike (N 45°E) and dip (75° NW) discordant to foliation were surveyed. These joints

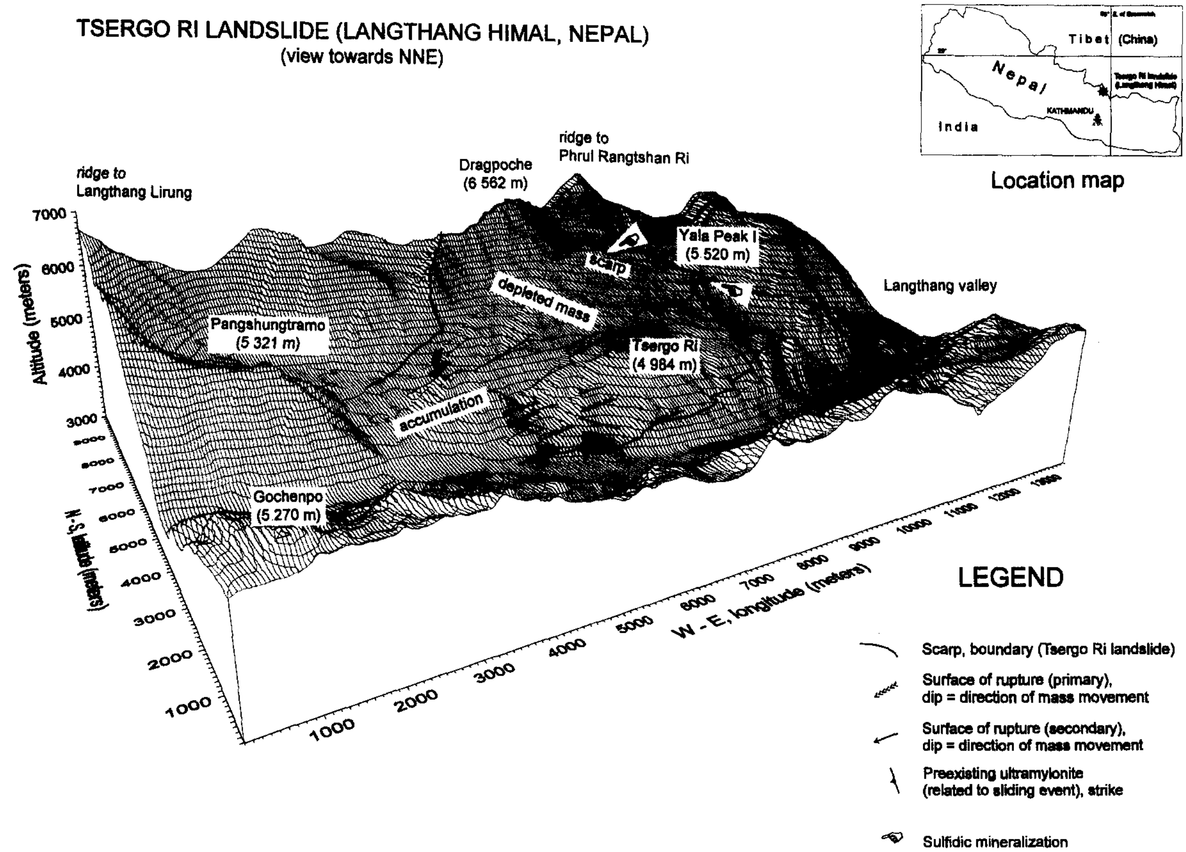

Fig. 9. Surface-plot of the recent geomorphological features of the Tsergo Ri landslide and surrounding areas, showing location of primary and secondary sliding planes or surfaces of rupture (= hyalomylonitic horizons, landslide-triggered) as well as preexisting (ultra)-mylonites (tectonic-triggered) with similar dips.

(average thickness 15 mm, maximum 20–30 mm) are filled with microcrystallized sulphides and are related to the main ore structure.

In addition related mineralization occurs south of the landslide area, at Gangtsa La (altitude 5150 m). Two concordant, tectonically controlled ore intercalations (situated 30 m and 130 m above recent glaciation) penetrate augen gneisses with similar generations of leucogranitic intrusions. Other points of sulphide mineralization are situated in the vicinity of Tilman's Col (uppermost section of the Langthang valley) and about 3 km ENE of Dragmarpo Ri, in the forefield of the eastern glacier. Two structurally controlled ore mineralizations outcrop at 5340 m (striking N 80°E, dipping 70° S) and 5400 m (striking N 0°E, dipping 85° E). The structural pattern, lithotectonic position and ore mineralogy correspond with the ore horizon at the Tsergo Ri landslide.

6. Ore breccias within the Tsergo Ri landslide deposit

South of Tsergo Ri, between Digyabsa and Tashigang, at 4500 m altitude, H. Heuberger and L. Masch (pers. commun., 1990) reported on one separate block of about 10^3 m^3 of brecciated and weathered ore within the landslide area. This deposit was interpreted as hydrothermally mineralized and compacted breccia, connected to a supposed tectonic fault in the Langthang valley. Weidinger (1992) detected further small outcrops of 'ore breccias' (max. volume 10–20 m^3) near Tashigang (alt. 4500 m), northeast of the Dzongdü (alt. 3970 m, 3990 m, 4090 m) and at the NW-wall of the Dranglung valley (alt. 4100 m). All points are near the sliding surface of the landslide, on top of the basement gneisses as intercalations of the

Fig. 10. View towards broken crest of the Tsergo Ri landslide between Yala Peak I (*YI*) and Yala Peak II (*YII*), showing the outcropping ore structure (*OS*) below both peaks. Discordant leucogranitic intrusions (*LG*). Neotectonic structures (*NS*). Gliding surface (*GS*). Background: peaks of Langthang Lirung (*L*) and Dragpoche (*D*). Location: about 1 km northeast of the Pijung alp, alt. 5200 m at the northeast ridge of the Pijung glacial cirque (*PK*), supposed prolongation of broken crest towards the southeast.

heavily brecciated hanging wall migmatites and granites.

The irregularly formed blocks have resisted weathering and erosion processes of the surrounding landslide material. The breccias principally contain fragments of quartz, granite, migmatite, gneiss (max. diameter 20–30 mm) and traces of primary sulphide ore. Red-brownish weathered matrix of secondary mineralization (mainly oxides), suggesting higher contents of ore, compacted and covered the angular components. Position and formation of these ore breccias indicate a material originated in structurally controlled ore outcrops near the broken crest. The material was dislocated, mixed up with bedrock during the landslide event, and subsequently compacted by weathering of sulphide ore due to mineralized groundwaters at the base of the landslide deposit. This consideration is supported by dating of the ore mineralization giving ages of galena in any case older than the landslide event (L. Masch, pers. commun., 1990).

7. Neotectonics

The Langthang area and surroundings are situated within a zone of highest uplift/denudation rates in the Himalayas. 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/year. Fission track data from the Nanga Parbat Haramosh Massif indicate higher uplift/denudation rates during the last 10 million years of about 5 mm/year (Zeitler et al., 1993; Chamberlain et al., 1995). Studies on the cooling history, sedimentology, oceanography, and palaeoclimatology suggest that rapid uplift and unroofing is not only restricted to those Himalayan areas. Across and within the India–Eurasia convergent zone, Dewey et al. (1988) reported on neotectonic displacement. Thus, in the Himalayas shortening values can be deduced from thrust zones of 18 ± 7 mm/year, and extension values from strike-slip faults of 10 ± 6 mm/year.

In the upper section of the Langthang valley a series of open joints and faults with the same orientation as leucogranitic intrusions, as well as the ore

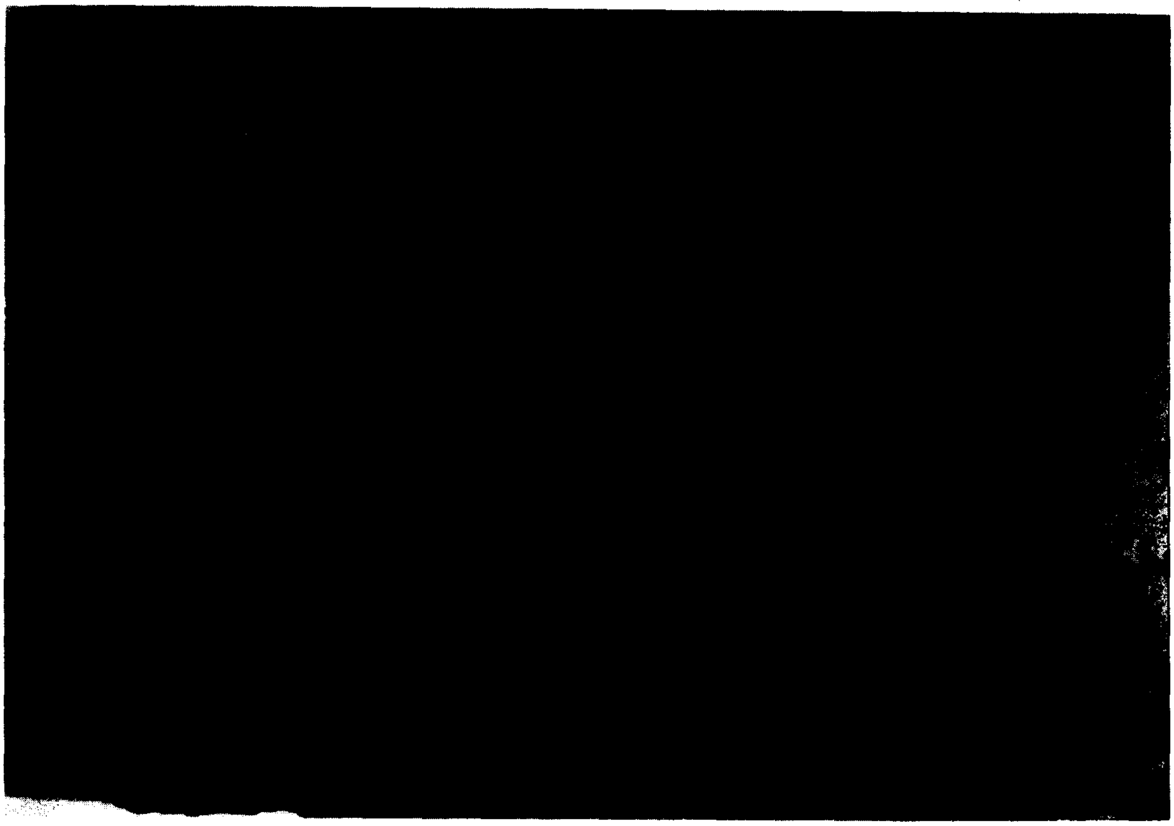

Fig. 11. Disseminated framework of pyrrhotite (*PYR*) from the lower part of the ore structure within leucogranites, along the broken crest of the landslide, between Yala Peaks I and II. Microcracks (*MC*) and joints partly filled with gangue (left and upper centre) and pyrite (*PY*) with skeletal growth (lower left corner), dip parallel or subparallel (flat and steep to SW) to movement direction of the landslide (*md*). See also Fig. 12. Location of sample: SSE-flank of the Yala Peak I, alt. 5465 m.

structure are evidence of neotectonic deformations. Due to statistical analysis of fabrics (joints, fissures, faults) these structures dip with varying degrees to the southwest and west within the gneissic base, but also in the vicinity of the broken crest of the landslide. With opposite dips (from SE to SSE) synthetic structures occur at the SE-ridge of the Pangshungtramo Peak and at the SSE-wall of the Dragpoche (Riedel shears). In any case these two assembled directions forced the scarp in its present curved shape and made the mountain range susceptible to movement beginning along initial joints.

8. New SEM- and EDX-data from the primary and secondary surfaces of rupture

Hyalomylonite, pumice, frictionite, and microbreccia from primary and secondary sliding planes of the Tsergo Ri landslide, as well as gneiss from the basement, have been analysed by means of SEM and EDX. Samples from the main sliding surface show spotted, breccia appearing, porous and mylonitic groundmass with insets of partially fractured quartz and feldspar grains. One grain of fractured quartz is affected by a well developed single set of lamellae with tiny inclusions, probably triggered by landslide dynamics (Fig. 13). Hyalomylonites frequently indicate cavities, also with fine pores (round or irregular), but not vent-like (with radially arranged fissures) as with 'Köfelsite' (Surenian, 1988). Pore sizes range in diameter from 1 to 500 μm, chiefly between 50 and 100 μm, rare in the mm-range (Fig. 14). Despite the partially molten hyalomylonite, the pumice samples of secondary sliding planes (southern flank of the Tsergo Ri) show an irregular frothy structure (Fig. 15), comparable

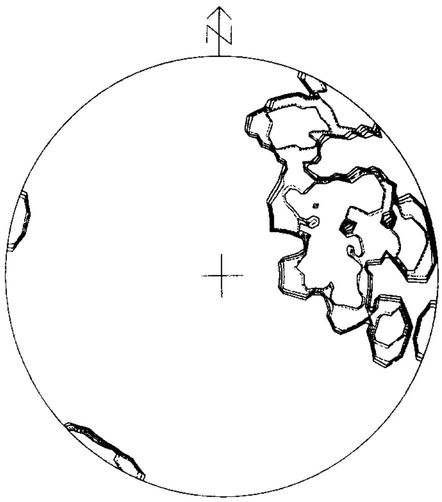

Fig. 12. Stereographic representation (lower hemisphere) of fabric data, surveyed at 5465 m, SSE-flank of Yala Peak I. Contoured density plot of 30 data points: orientation of active joints and veinlets filled with gangue, pyrrhotite, and pyrite within the ore structure.

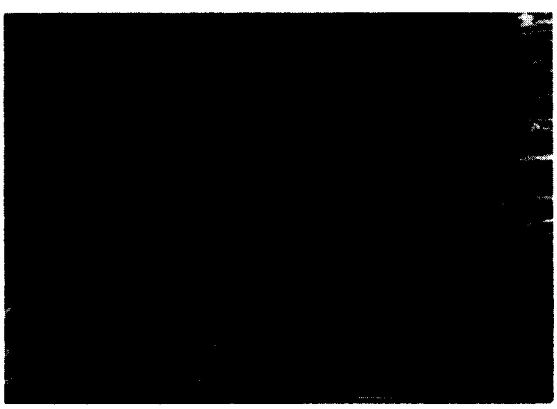

Fig. 13. SEM-photograph of a quartz grain with a single set of lamellae and tiny inclusions. Fracture pattern triggered by landslide dynamics. Location of sample: erosion trench, about 550 m northeast of the Langthang 'airstrip', Tsergo Ri S-flank, alt. 4010 m.

Fig. 14. SEM-photograph of hyalomylonite (porous frictionite) from primary sliding surface. Notice small number of disordered cavities. In contrast to 'Köfelsite' (Tyrol, Austria) and pumice from secondary sliding surface (cf. Fig. 15), interconnections of individual bubbles scarcely visible. Location of sample: erosion trench, about 550 m northeast of the Langthang 'airstrip', Tsergo Ri S-flank, alt. 4020 m.

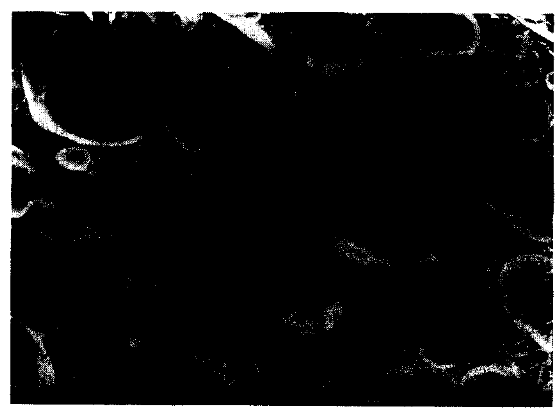

Fig. 15. SEM-photograph of pumice like hyalomylonite from secondary sliding surface. Through its porous structure, this frictionite bears a close resemblance to the 'Köfelsite'. Location of sample: erosion trench, about 700 m southwest of Tsergo Ri, Tsergo Ri S-flank, alt. 4610 m.

and similar to the Köfelsite model. A view to the formation of texture and deformation structures of included quartz and feldspars (after etching with hydrofluoric acid, and analysed by EDX) has so far only shown deformations triggered by tectonic stress or landslide dynamics, such as apparent sharp cracks in different directions ('dislocations'), forming a single and straight set, and mostly curved, irregularly developed and not sharp sets of lamellae (comp. Officer and Carter, 1991). Sillimanite–gneiss samples of the basement also indicate a disordered structural model and deformation structures caused by tectonic stresses and landslide dynamics (Fig. 16). Structures which are only explicable to shock metamorphism, as described from the 'Köfelsite' (Surenian, 1988), could not even be observed with etching (hydrofluoric acid) in all samples of the Tsergo Ri landslide. Thus, there is so far no evidence of an extraordinary event (meteoritic impact) causing the giant landslide.

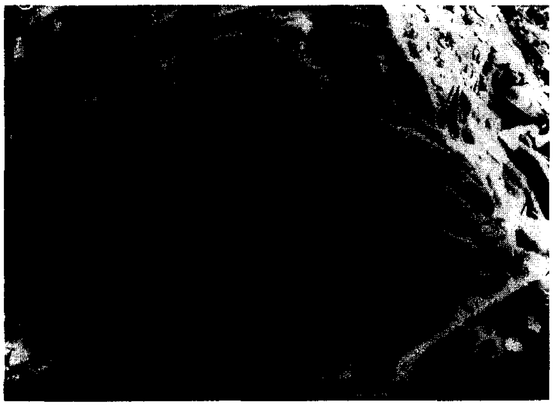

Fig. 16. EDX-analysed sillimanite–gneiss sample from the basement of the Tsergo Ri landslide: curved lamellae visible in a quartz grain, triggered by tectonic stress and landslide dynamics. Location of sample: eroded part of landslide deposit, about 500 m northeast of the Langthang 'airstrip', Tsergo Ri S-flank, alt. 4100 m.

9. Seismic activity

Seismic activity as the triggering causal factor for the landslide event is primarily suspected. Pseudotachylites within the landslide area give evidence for palaeoseismic events related to overthrusting. One single phase of movement on the MCT and two coeval ones together with the Main Boundary Thrust (MBT) document decreasing displacement rates on the MCT, shifted to the structurally lower MBT (Hodges and Silverberg, 1988; Macfarlane, 1993). Supposing progressive seismo-tectonic activity towards the south (e.g., MBT) within the Himalayas seems to be realistic, as proved by the distribution of earthquakes in the youngest geological past (Dewey et al., 1988). Mugnier et al. (1994) reported on neotectonic displacement at the MBT. Seismic records document earthquake events with intensities up to 8.6 (Richter scale) within the historic past, and a periodicity (major earthquakes) of about 30 years (Sharma, 1990). Assembled with the preparatory causal factors such as the ultramylonitic and pseudotachylitic horizons, leucogranitic intrusions, slickensides, sulphide ore structure associated to leucogranites, neotectonic structures, and high relief, a seismic event might have shifted the slopes from a marginally stable to an actively unstable state and thus might have initiated the mass movement.

10. Conclusion

The described facts point to a causal connection between leucogranitic intrusions, subsequent tectonic deformation and sulphidic ore structures within the Tsergo Ri landslide event. Remarkable correspondence between leucogranitic dikes and associated ore-bearing structures with the broken crest or scarp, as well as their dip being the same as the direction of the landsliding, are significant, although the disseminated horizon runs partly below Yala Peaks I and II. This relating mountain crest could resist the slope failure due to different rheologic properties of the ore body and adjacent high-grade metamorphic rocks. Ore-compacted breccias on top of the primary sliding surface within the landslide deposit attest dislocation and destruction processes of the ore body during the sliding event. Ore paragenesis and genesis indicated the leucogranites as the source of the mineralization. SEM and EDX studies on samples of hyalomylonite from primary and secondary sliding planes give no evidence of any kind of shock metamorphism (impact), focusing seismic activity along MCT and within the High Himalayan Crystalline as the triggering causal factor. Conditions conducive to the Tsergo Ri landsliding are: (1) weak quality of disseminated mineralized rocks, which were subsequently weathered, (2) rheologic brittle reaction of granitic intrusions (with mylonites and slickensides) associated with neotectonic stress release, (3) different stress behaviour between metasediments and granites, and (4) palaeoseismic activity (pseudotachylites).

Lacking ore horizons (SSE-wall of the Dragpoche) assist in improving the rock quality. Prolongation of the ore structures to the northeast (Phrul Rangtshan Ri) gives an idea of the whole former sliding area (collapsed in situ to the valley of Phrul Rangtshan Tsang).

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