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Primary sliding mechanisms in dipping interbedded conglomerates and marls

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ABSTRACT: In May of 1999, melting snow cover combined with heavy rainfalls in the northeastern part of Switzerland resulted in the occurrence of numerous shallow landslides. Many of these slides were located in the subalpine Molasse, a series of interbedded marls, conglomerates and sandstones. The subalpine Molasse is highly prone to such sliding activity given the dip of the bedding, the surface topography and the weak nature of the marls that rapidly degrade when exposed to weathering. Historically, the subalpine Molasse has hosted numerous slides of varying orders of magnitude and the surficial morphology is primarily dictated by previous rock slides which periodically reactivate as secondary soil slips. Given the conditions contributing to the slope failure and the history of previous sliding, similar slides within the region are highly probable. This paper presents the findings from a detailed investigation of one such site, the Rufi slide.

1 INTRODUCTION

Melting snow cover combined with heavy rainfalls in the year 1999 resulted in over 350 recorded landslides and debris flows in Switzerland (Lateltin et al. 2001). These slides resulted in 2 deaths and over 100 million SFr in direct losses. In the prealpine belt of northern Switzerland numerous shallow landslides occurred in the subalpine Molasse, a series of interbedded marls, conglomerates and sandstones. The subalpine Molasse is highly prone to such sliding activity given the dip of bedding and the surface topography.

Historically, the subalpine Molasse has hosted numerous slides of varying sizes. Heim (1932) describes numerous slides involving the conglomerates of the subalpine Molasse (“Nagelfluh”). Most of these instabilities involve the breaking off, toppling and/or sliding of conglomerate blocks, which collect over time as debris at the foot of the slope. If adverse groundwater conditions were present and the slope of piled-up debris was steep enough, these “debris streams” as they were termed by Heim would reactivate to form a debris slide/debris flow.

Probably the best-known failure in the subalpine Molasse was the Goldau rockslide (also referred to as the Rossberg slide or Goldauer Bergsturz). The 1806 failure claimed 457 lives when a slide involving 20 million m^3 of rock was triggered by a rapid snowmelt coinciding with heavy rainfall (Eisbacher & Clague 1984). The slide mass primarily consisted of conglomerate beds dipping between 15º and 30º, failing along bedding plane contacts with the underlying marls (Fig. 1). Given the kinematic feasibility promoted by the geological conditions, it isn’t surprising that earlier failures preceded the 1806 event, including one in 1354, and that remnants of prehistoric slides cover the lower Rossberg slopes (Eisbacher & Clague 1984). Following the 1806 event, smaller slides have also occurred, notably in 1874 and 1910, the latter involving the reactivation of old slide debris (Heim 1932).

Given the propensity for failures in the bedded rocks of the subalpine Molasse, a detailed investiga-

Figure 1. Lateral release margin at the top of the Goldau rockslide showing interbedded conglomerates and marls dipping at angles between 15º and 30º.

tion of one such slide, the 1999 Rufi slide, was conducted immediately following its occurrence. This allowed for detailed mapping and analysis of several preserved features characteristic of shallow sliding masses, thus providing key insights into the geological and geomechanical factors contributing to the slide.

2 THE 1999 RUFI SLIDE

The Rufi slide is located near the town of Rufi in the Canton St. Gallen in north-eastern Switzerland. As previously noted, the year 1999 in Switzerland was marked by extraordinary precipitation events. Most notable were heavy snowfalls that fell in the Alps over a 4-week period towards the end of January and into February, and strong rainfalls experienced in May. The latter produced considerable flooding and landsliding. The primary events of the Rufi slide occurred during this period on the night of May 13th.

The slide events involved the mass movement of surficial soils, weathered slide debris (accumulated from previous slide events) and intact rock, over a down slope distance of approximately 800 m (Figs. 2-3). According to local reports, the primary rockslide occurred suddenly overnight carrying with it a 30 m stretch of road. Asphalt from the road was found 150 m downslope (Fig. 4). The failed mass then came to rest on top of an older inactive debris slide, also saturated by the heavy precipitation, reactivating it. Damage resulting from the reactivation of the lower debris slide body was mostly in the form of destroyed or disturbed forest and pastureland. Total damage relating to the slide included the destruction of a paved road and 1 km^2 of forested and pastured land.

2.1 *Geological setting*

The Molasse basin of northeastern Switzerland consists of thick beds of detrital sediments deposited during the alpine emergence in the Alpine foreland trough. Its greatest thickness reaches 5000-6000 m along its southern margin below the front of the Alpine nappes (Trümpy 1980). The subalpine Molasse forms the transition between the thrusted alpine nappes of the Helvetic belt and the flat-lying Molasse. The subalpine Molasse units are strongly overthrusted and generally consist of thick slabs of conglomerates (“Nagelfluh”), dipping SE between 20º and 80º, which act to build-up entire mountains. These conglomerate beds are generally several meters thick and alternate between sequences of thin sandstone and marl beds.

The rock units found in the Rufi slide area consist primarily of Tertiary sediments from the deposits of the lower Freshwater Molasse (Upper Oligocene and early Lower Miocene). These sediments were deposited within a continental alluvial fan environment and consist of a series of interbedded conglomerates, sandstones, and marls (Fig. 5). The conglomerates make-up approximately 50% of the conglomerate-sandstone-marl sequence thickness. Most of the clasts in the conglomerate are derived from dolomites and limestones from the prealpine nappes, and show fining upwards. The relative strength of the conglomerates makes them more resistant to weathering resulting in the formation of cliffs with heights of 2 to 20m (Fig. 6). The sandstone consists of coarse-grained, cross-bedded lime sand. It appears gray in colour when weathered and brown when fresh. The marls are gray to bluish gray in colour and are highly susceptible to weathering. Laboratory testing shows that the carbonate content of the marls belonging to the Rufi slide is in the range of 40 to 50%.

The tectonics of the investigation area are representative of the subalpine Molasse, consisting of thick over-thrusted layers which were pushed over by the folded Helvetic nappes. For this reason, the different tectonic units are easily differentiated. In the slide area the bedding layers dip to the southwest and are cross-cut by near-orthogonal joint sets (Figs. 6-7). These joints, found primarily in the con-

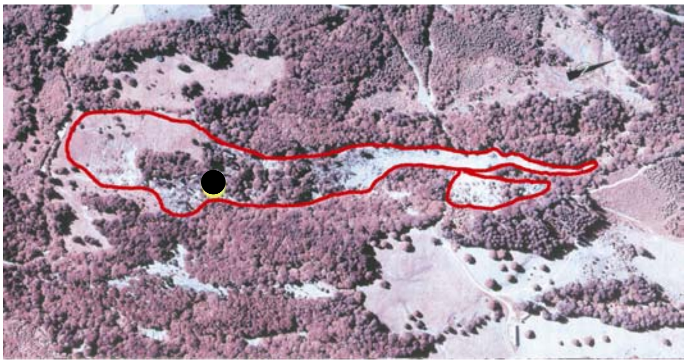

Figure 2. Airphoto of the 1999 Rufi slide, outlining the slide boundaries (after Bollinger et al. 2000).

Figure 3. Travel path of the 1999 Rufi slide.

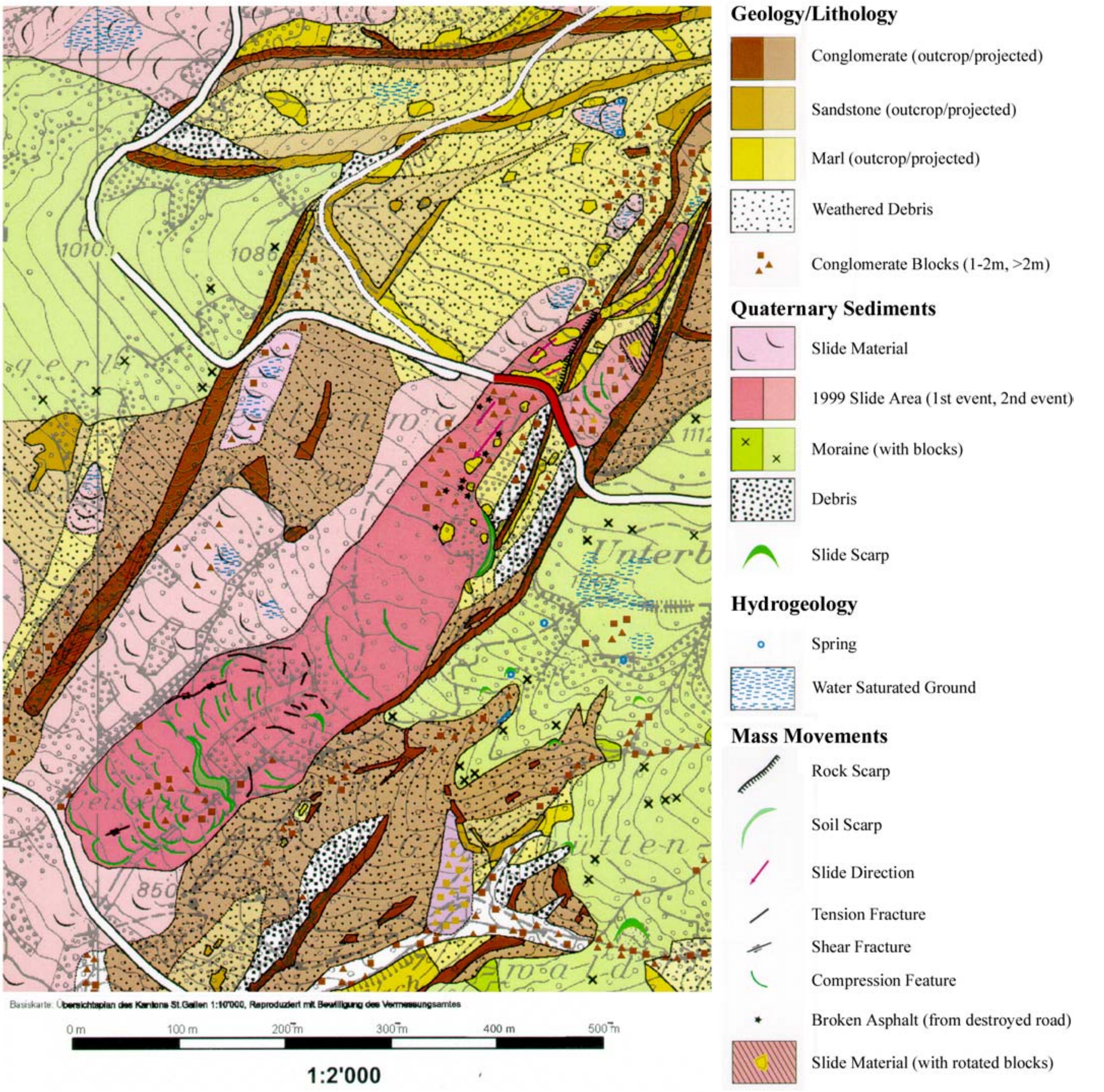

Figure 4. Detailed geological map of the Rufi slide area (after Luginbühl 2001).

glomerate and sandstone units, play a major role in promoting instability.

Morphologically, numerous debris fans cover the slopes (Fig. 4). The debris consists of weathered material and deposits from smaller block falls. These deposits are mostly found at the foot of conglomerate cliffs. Below the vegetative cover, most of the investigation area is covered by weathered/ancient slide debris, especially over the lower halves of the slopes. Numerous signs of subsurface creep are observable in these areas.

2.2 *Site hydrogeology*

Surface drainage in the area runs north-east to south-east eventually draining into the Linthebene River and afterwards into Lake Zurich. The subsurface material typically consists of jointed rock cover and weathered debris. Infiltration occurs in the upper slopes where the permeability in the underlying bedrock is largely joint-controlled. Vertical joint systems in the thick conglomerate sequences (Fig. 6) allow for easy infiltration and circulation of groundwater. Underlying marl layers act as aquitards. Fracture systems in the conglomerate layers together with the interbedded sandstones also help to

Figure 5. Bedding sequence of the interbedded conglomerates and marls along the margin of the Rufi slide.

Figure 6. Cliff-forming conglomerates showing subvertical joints.

store large volumes of water when frozen during the winter months. Upon thawing, the water is released to drain along the orthogonal fracture systems and their contact with the impermeable marls. Flow anisotropy in the subsurface due to lithology changes, structure or weathering results in the formation of numerous springs. Weathered debris material in the lower sections of the slope is found to be highly impermeable owing to the large proportion of silts and clays that the rocks break down into.

2.3 *Historical slide events at Rufi*

Prior to the 1999 event, a history of previous instabilities had transpired influencing the composition of the 1999 slide mass. Numerous indications of post-glacial slide events can be found in lower sections of the slope, one dating back 800 years (as determined through tree dating by Bollinger et al. 2000; the black solid circle in Fig. 2 marks the location where the date was derived). The first recorded slide at the Rufi site, as noted by local residents, occurred around 1900. To stabilize the slope, a surface drainage system was constructed.

Given this history of previous sliding, activities along the slope can be described as a series of retrogressive, multiple translational slides. The material found along the profile of the slope thus involves undisturbed, in-place rock in the upper sections (interbedded conglomerates and marls) and weathered, disturbed debris along the lower sections. The 1999 slide reflects this complexity, and can be viewed as a composite slide for which two events involving different materials can be discerned. The first event was the planar failure of mostly intact rock from the upper sections of the slope. The second was the reactivation and failure of weathered slide debris on which the initial failed rock mass slid onto.

2.4 *Triggering event*

Triggering events can be envisioned as linking cause and effect. For Rufi, the cause can be attributed to several geological factors and processes (discussed in the next section) and the effect was obviously the 1999 slide event. The trigger that initiated the Rufi slide was an intense precipitation event coinciding with those that fell throughout Switzerland that spring. Precipitation records for the Rufi area show that two intensive precipitation events occurred on May 12^{th} and 21^{st}, involving rainfalls of almost 100 mm in a 24 hr period (Fig. 8). The primary Rufi slide occurred following the first of these two events on the evening of May 13. In terms of relative magnitude, it can be noted that monthly precipitation totals for February and May 1999, exceed their yearly averages. In the one-week precipitation period preceding failure, approximately 200 mm fell. These in-

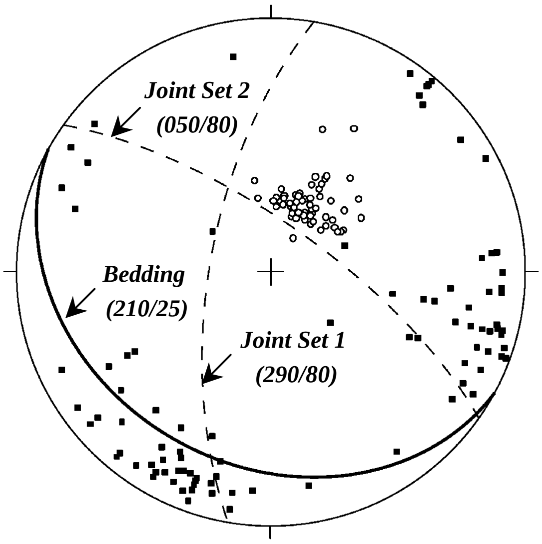

Figure 7. Equal area stereonet plot of discontinuities measured along the Rufi slide boundaries (○ = bedding plane; ■ = joint; dip direction/dip).

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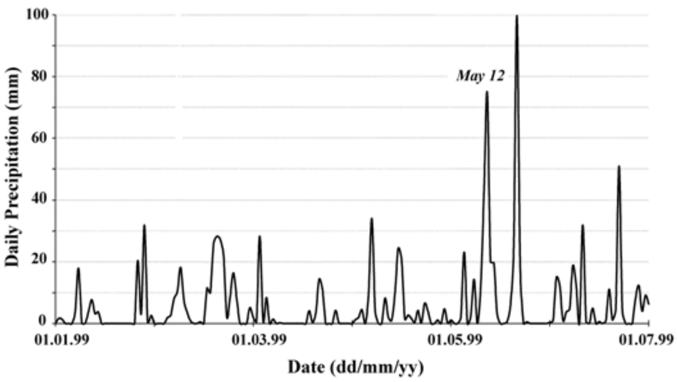

Figure 8. Daily precipitation records for the Rufi area during the first half of 1999.

tense precipitation events likely also led to the release of large water volumes through accelerated snow and ground thaw, thereby both saturating the marls and increasing water pressures along open fractures.

3 PRIMARY SLIDE MECHANISMS

Examination of the pre-failure slope conditions suggests that the uppermost sections of the slide mass involved a narrow segment of interbedded conglomerate and marls. Contrary to reports involving other slides in the subalpine Molasse, where the contact between the conglomerate and the underlying marls was assumed to form the failure surface (e.g. the 1806 Goldau slide), observations at the Rufi site indicate that the slide surface passed primarily through the marls. Furthermore, these observations suggest that the slide surface occurred along a weathering boundary within the marls, separating the upper highly weathered layers from the underlying unweathered layers.

Examination of the slide scarp and lateral boundaries indicates that the thickness of the conglomerates was approximately 2 m at the head of the slide. It is at the back scarp that the slide surface most closely coincides with the contact between the conglomerate and marl. The sliding surface in this upper section is planar dipping at approximately 22˚. Moving down slope, the slide surface slowly cuts down into the marls in a step-like fashion (Fig. 9) over a slope length of 100-200 m.

3.1 *Weathering profile of marls*

Detailed mapping and laboratory analysis was performed on the weathering characteristics of the Rufi marl. As noted above, the weathering profile and degree of weathering in the marl beds was found to closely control the development of the failure surface along the upper sections of the Rufi slide. Figure 10 shows the weathering profile derived for the marls in the slide area based on designations by Einsele et al. (1985). The degree of weathering of the marl below the slide surface was characterized as W1 (slightly weathered). The upper marl layers constituting the slide body range in their weathering state from W2 to W5 (moderately weathered to residual soil). Field observations suggest that the more defined the weathering contrast between the marl layers, the greater the tendency for overlying conglomerate blocks to creep along the weak interfaces or incompetent layers (Fig. 11).

Weathering of the marls involves both physical and chemical processes. Physical weathering appears to involve material strength degradation through wet-dry cycling, freeze-thaw cycling, and swelling pressures created by the clay fraction in the marls. In general, wet-dry cycling may be considered limited in depth of penetration to areas immediately neighbouring fractures in the otherwise low permeable marl. However, fracture permeability and connectivity are not deemed entirely necessary as wet-dry cycling can still be promoted through pore water content fluctuations over large periods of time. The penetration depth of frost action may also be limited, but in the pre-alps can reach depths of 120 cm (Prinz 1997). Physical weathering through swelling pressures generated by clay minerals is attributed to Montmorillonite found in the marls. Chemical weathering also contributes to the strength degradation of the marls layers, primarily in the form of rock reactions with water, acids, salts and gases.

With weathering comes further strength degradation of the over-consolidated marls in the form of fractures opening along bedding planes and other tectonic structures in the marls. These features then

Figure 9. Upper Rufi slide surface through marl layers.

help to promote further weathering within a shorter time period, increasing the degree of segmentation between layers within the marls. Field observations suggest that these processes were the controlling features with respect to how deeply the slide surface cut down into the marls.

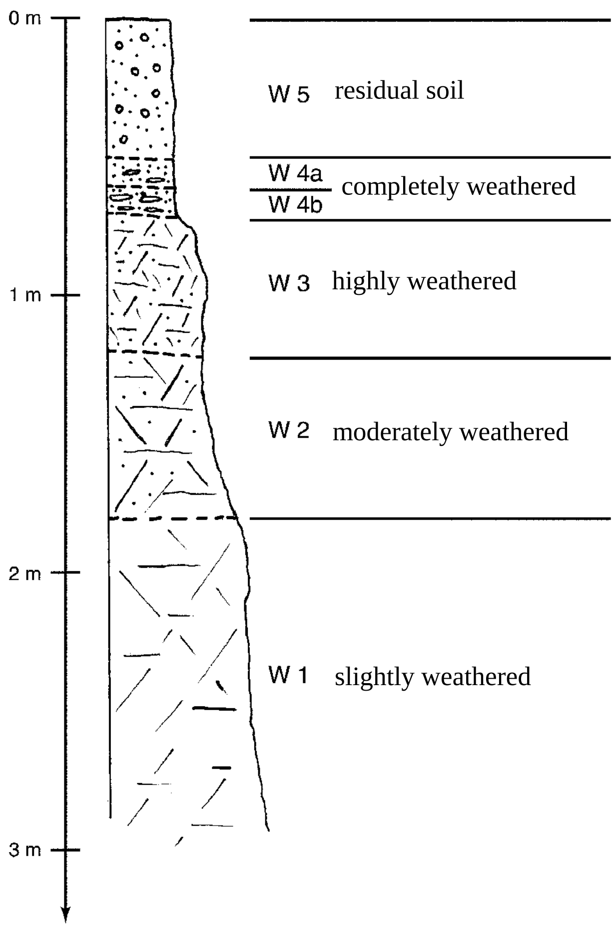

Figure 10. Schematic diagram of the weathering profile mapped in the Rufi slide area.

Figure 11. Conglomerate block overlying weakened weathered marl.

4 CONCLUSION

Results from a detailed mapping investigation show that problematic instabilities in the subalpine Molasse are largely due to adverse dipping of interbedded conglomerates and marls. Primary sliding can be attributed to strength degradation in the marls due to weathering processes and saturation during periods of heavy precipitation. Field observations reveal that these processes control how deeply into the rock mass the slide surface cuts. Furthermore, continued weathering of the slide debris can lead to secondary sliding in the form of small soil slips. Thus, understanding these weathering processes and their temporal and spatial evolution, is necessary for hazard assessment of those slopes neighbouring the failed Rufi rock mass.

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