Rock Falls and Landslides in the Alps in the Past 15,000 Years

by Arne Grobe (AGW 4th semester, M.Nr. 280004), August 2013

Summary:

Rocks falls and landslides have affected the Alps mainly in the past 15,000 years. This work is giving an overview of the history of this period and discusses the relevant general weathering and erosional processes that are important for slope stability. Besides, general slope processes of the Alps are discussed with the Flims and the Pizzo Cengalo rock falls and the Val Pona landslide acting as examples. Moreover, the risk assessment procedures are elaborated.

As this paper was written as part of the Alps Excursion 2013, of the institute of Structual Geology, Tectonics and Geomechanics and the institute of Geology and Geochemistry of Petroleum and Coal, references to visited sites appear every now and then.

Content

I. Chronostratigraphic Overview 1
II. Weathering Processes.....2
III. Erosion of the Alps 3
IV. Gravitational Processes 3
V. Slope Stability 3
VI. Rock Fall Periods in the Alps 4
VII. Slope processes in the Alps.....5
VIII. Example 1: Flims Rock Fall.....7
IX. Example 2: Pizzo Cengalo 7
X. Example 3: Val Pola Landslide...8
XI. Risk Assessment 8
References 10

I. Chronostratigraphic Overview

To get an idea of the paleo environment of the last 15,000 years the chronostratigraphy of the Late Quaternary will be outlined first.

The main interval of the past 15,000 years is named Holocene (11,700 y ago until present, International Commission of Stratigraphy, 2011). The previous chronostratigraphic series is the Pleistocene (2.6 Ma b.p. – 11,700y b.p.). Its beginning is marked by a worldwide drop in temperature and increasing glaciation (Kuhlemann et al., 2002). The whole Pleistocene was dominated by rapid changes of warm periods and interglacial times accompanied by contemporaneously accelerated erosion by the ice masses. Pleistocene's latest stage, the Late Pleistocene, is called Weichselian in North West Europe and is representing the last

interglacial time on earth (ICS, 2011). Within this time, the last glacial advance reaches Europe from the north until the state of Mecklenburg-Vorpommern in Germany. Due to this, the time span from 15,000 to 12,500 y is also named the Mecklenburg phase of the Weichselian interglacial. Since 12,500 y it is stated as Late Glacial Weichselian. Even if glaciers are still covering parts of Northern Europe at this time, the main landmasses of the continent have already been ice free (Lasberg and Kalm, 2003).

The year 15,000 before present is internationally accepted as time in which the climate was warm enough for the entering of modern human beings to Europe (Andel, 2002). In addition, this time represents the era were the coverage of ice shields have left the Alpine region. As a consequent to the lack of weight the Alpine region has been uplifted in isostatical compensation for additional 150 m. This process is still ongoing (Kuhlemann et al., 2002).
Contemporaneously, plate doming, in the order of some meters, occurred in the foreland of the glaciers due to compensation movements of the stiff plate (Pfiffner, 2010).

Delacou et al. (2004) and Calais et al. (2002) stated that the stress regime in the Alps is and were mainly of extensional character since the Miocene. The extensional belt is basically following the "large-scale topographic crest line of the Alpine arc" (Delacou et al., 2004). Exemplary, the central part of the Alps shows an east-west extension of 1 mm/y. Compression from northwest to southeast is observable in the southern part of the Alps only (Calais et al., 2002).

II. Weathering Processes

After this short excursus to the latest earth history, we will have a look at the fundamental processes of weathering that are important in the Holocene alpine region.

In general, the processes are subdivided in physical and chemical weathering. For former named ones, all processes triggered by changes in temperature and volume account. As a rule of thumb, normal daily temperature changes can affect the upper 50 cm of the ground and yearly changes can influence the upper 20 m. Due to different expansion coefficients of different minerals, rocks or water present in the rock, temperature changes induce internal stress (Bahlburg and Breitkreuz, 2008). If this stress is exceeding the rock's failure criterion it will crack. After the occurrence of first cracks, water can enter the generated flow path and widen them. Thereby, the rock stability is reduced even more and the risk of a matrix breakdown will rise.

Another important physical factor is frost weathering. During the change from water to ice the volume is increasing up to 9 %. If this process takes place in cracks or faults, it will accelerate the process of weathering significantly and can act as triggering mechanism for single rock falls. An additional accelerating factor can be the presence of single trees (biological-physical weathering); their roots can create additional flow pathways for water or air.

The chemical weathering in the Alps is mainly represented by solution weathering of carbonatic layers which can be seen as minor important for rock falls and land-slides (Bahlburg and Breitkreuz, 2008). Nevertheless, swelling of clay, as a result

of the reaction with water, can decrease the shear strength of a matrix and trigger gravitational movements (Varnes, 1984).

III. Erosion of the Alps

These weathering processes result in the surface erosion of the Alps. Strongest evidence for erosion in the past is given by the lack of several kilometers of metamorphic rocks on top of the recent surface. The biggest abrasion took place during Cretaceous and Cenozoic times, where the orogenesis created uplift. Even if the erosion rates are lower at present times the process is still going on (Pfiffner, 2010). The recent erosion rate can be calculated out of the sedimentary runoff. This is best done at the four biggest rivers exiting the Alps: Rhine, Rhone, Danube and Po. Jäckli (1958) measured the sedimentary load of the first two rivers and calculated an average erosion rate of 0.5 mm/y.
At this point it has to be mentioned, that main erosion took and takes place during single events, mainly strong rain or flooding events. Therefore, the erosion rate will be influenced by several peak erosion phases and is not constant over the year.

IV. Gravitational Processes

The discussed weathering processes and erosion are observable in several gravitational phenomena. Due to morphologic leveling by the Pleistocene glaciers, all detectable alluvial fans represent accumulations of the last 15,000 years (Pfiffner, 2010).

Several gravitational erosion processes can be found in the Alps. Important ones are landslides, which are in general covering a large area and are relatively slow processes at the beginning, out of which very fast rock slides or falls can develop. If loose sediment is transported only, the terms slumping or slump flow are used as well. These fast slides account for “one of the most threatening natural hazard in certain mountainous regions” (Crosta et al., 2004). Based on the grain size of the particles, it can be further divided in grain- or debris flows. If rock falls are developed, they are locally appearing phenomena of single falling rocks or rock units at steep cliffs. As well as rock slides they can develop out of landslides or can occur at the same time; e.g. if the first block of a landslide is breaking down (Bahlburg and Breitkreuz, 2008). Nevertheless, the termini have to be used with caution: Especially in non geological acquaintances, the term landslide is often used in general for all slope instabilities (Varnes, 1984).

V. Slope Stability

For the understanding of these processes, happened geo hazards have been analyzed by geologist and geographers. Based on their work the most important parameters influencing the slope stability can be named. First of all, the equilibrium of steep slopes, as they are often observable in the Alps, are in a critical stability condition or even in a meta stable state (Pfiffner, 2010). This equilibrium can easily be disturbed by:

1) Slope movement induced by pressure release of deglaciation,

2) earthquakes or vibrations (may be released by human beings/construction sides), and

3) reduction of friction by circulating waters (Pfiffner, 2010).

To put this in a physical background Coulomb defined the critical shear strength in his failure criterion as:

$$|\tau| = c + \mu_i{}'\delta_n$$

This linear equation depends on the cohesion (c), as the intercept of the y-axis, the internal friction ($\mu_i{}'$) as slope and the normal stress (δ_n) as x-value (dashed line *Figure 1*). Based on this formula the rock is strengthened with an increase in pressure or normal stress respectively (Lockner, 1995). The theory was later developed by Mohr to his failure envelope and is illustrated with Mohr circles in a plot of shear stress vs. normal stress (*Figure 1*, Lockner, 1995).

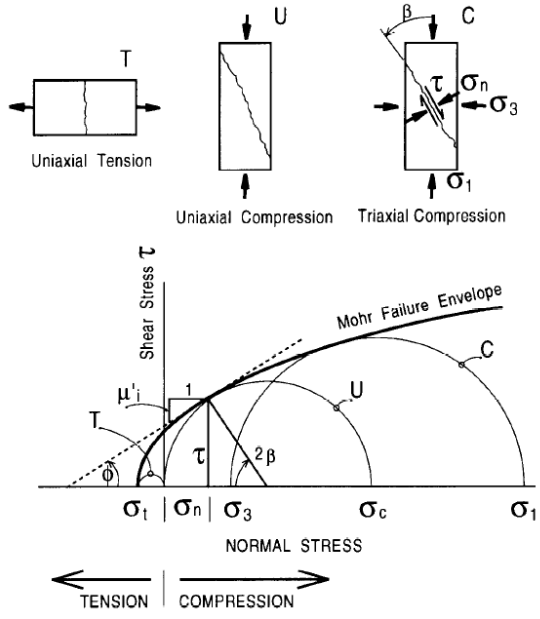


Figure 1: *Mohr failure envelope showing the relationship of stresses and failure parameters for 3 examples: One for tension (T) at negative normal stress and two (uniaxial U and triaxial C) for compression at positive normal stress values. Additionally, the Coulomb failure criterion is shown as dashed line (---). Also internal friction, shear stress and the angle beta are illustrated. (modified after Lockern, 1995)*

Again the slope is defined by the internal friction and the slope angle of the curve represents the angle of this internal friction. The circles' radius is defined by maximum and minimum normal rock stress. Whereby, the angle between the orthogonal line on the failure envelope to the x-axis is defined by 2β, describing the doubled angle between failure plain and maximum stress obtained.

If a defined circle hits the Mohr failure envelope the rock formation will break down. Thereby, positive values of the normal stress correlate with compressional and negative ones with tensional processes. For example, an increase in pore pressure, triggered by the inflow of water, will shift a drawn circle to the left. By this, it will get closer to the failure line and the rock stability is decreased.

VI. Rock Fall Periods in the Alps

In the Alps two phases have been identified in which happened rock falls cumulate: During the Boreal between 9800 and 9200 y four major rock falls took place. The Flims, Kunkels and Kandertal slide in the Central Alps and the Köfels slide in the Eastern Alps (*Figure 2*). A second phase of major rock falls was dated between 4200 and 3700 y before present (Subboreal) and affected mainly the Eastern Alps (Pfiffner, 2010). First interpretations of Gruner (2006) (stated in Pfiffner, 2010) correlated these events with the rainy periods of the cold phases during Boreal and Subboreal. Pfiffner (2010) countered that based on this theory the main cold period of the Holocene between 8200 and 200 years before present should represent major landslides as well.



Figure 2: *North oriented map of the Alps with highlighted, here mentioned rock falls (red) and the Val Pola landslide (blue). Country boarders are indicated as yellow lines and main cities are shown as red spots. (modified after a map of Google Earth, 2013)*

However, this is not the case. Only the Totalp rock fall accounts for this period and this may be a coincidence.

Based on the rock fall's ages, the above named reason of deglaciation (1) did not apply to them. At the time of the rock falls the land-covering glacier masses have already been deglaciated. This can be assumed for nearly all of them in the Alpine region (Pfiffner, 2010).

At recent time it seems that a new, third time of excessive occurring rock falls is reached. Impressive examples are the rock falls of the Pizzo Cengalo (3 Mio m³, 2011) and of Al Gal (2004). First scientists correlate these events with the melting of the Alp's internal permafrost. Modeling of permafrost as remnant of the last glacier time in the Alps combined with climate data shows that the times of major permafrost melting correlates with recent time.

VII. Slope processes in the Alps

To get a more detailed understanding of the processes we will have a closer look at them in the following.

For the slowly, gravitational gliding of slopes two major kinds are existing. Both mainly depend on the underground and therefore on the rock type (e.g. cohesion, internal friction) and the orientation of bedding and cleavage (often influencing the angle β). The base of the rock slide is, in both cases, represented by one main fault (*Figure 3*). In addition, ridges develop on top of the slope (sometimes

over several km in length) and the upper end of the slide is marked by opened cracks in the ground. This phenomena was observable during the Alps excursion e.g. at the moraine of the Monteratsch Glacier at the Diavoleza. Furthermore, the first case (*Figure 3*, *a*) is characterized by gently dipping bedding or cleavage and antithetical normal faults develop, dipping perpendicular to the orientation of the slope. The faults result in an elongation of the moving mass and produce small, symmetric ridges on top of the slope. The second case (*b*) mainly develops on nearly vertical dipping underground (*Figure 3, b*). Steep faults occur and the down-sliding blocks could show an additional rotational movement. In this case, the resulting ridges are mainly asymmetric and produce steeper counter slopes. For risk assessment both cases can result in very rapid events that can be released in time spans of hours.

The first case could easily develop fast sliding movements if water is entering the faults. The second case is more affected by the fast inflow of air: In the moment where a crack is getting to wide, air will flow in immediately and shift the Mohr's circle to the left, resulting in rock failure and often rock falls. During winter times the above explained process of ice decompression can get important as well. Both will mainly result in major rock falls.

As good indicator for slope movements *Säbelwuchs* occur (*Figure 4)*. This german term defines trees affected by slobe movement. To compensate their basis' dislocating rotation they change their growing direction vertically.

Based on the dependency on the underground, the risk potential is varying slope to slope and it is hard to give one assessment only (Pfiffner, 2010).

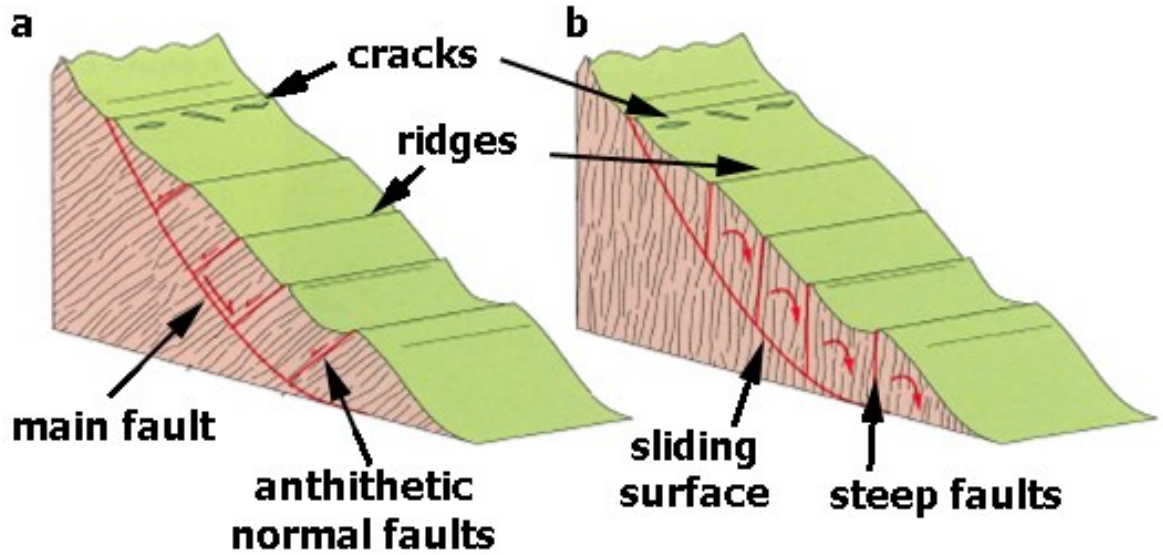


Figure 3: *Illustration of the two gravitational gliding processes: a) Showing gently dipping of layer and/ or cleavage with elongation of the moving mass and b) showing steep dipping with the generation of different rotating blocks.(modified after Pfiffner, 2010)*



Figure 4: *Indicator of the slowly gravitational slope movement: The tree's basis is moved and it turns it growing direction to an upward position (dtsch. Säbelwuchs). Picture taken on the way to the Refugio Sciora.*

VIII. Example 1: Flims Rock Fall

The biggest rock fall of the Alps is represented by the rock fall of Flims. We will describe and discuss it here to illustrate the data collection with an example. Additionally, its debris fan was visited during the Alps Excursion. The event took place 9300 years ago in the Rhine valley at the small town of Flims, approximately 70 km SE of Zurich, Switzerland (*Figure 2*). The generated alluvial fan covers an area of 30 km² and by this, accounts for one of the biggest rock falls worldwide. The fallen mass is characterized by a maximum thickness of 1 km in the middle. Based on an average thickness of 500 m, Pfiffner (2010) calculated a moved volume of 15 km³. This volume was released in one piece, whereby some parts were smashed down by the collision at the other side of the Rhine valley. By this, the river flow was stopped and piled up as the Lake Illaner. This resulted in a second geohazard: A flood was generated in the moment in which the piled-up water masses have reached the top of the dam overflow it and broke it down. In the last 9000 years, a 300 m deep canyon, the Ruinaulta, developed through the masses of the rock fall of Flims (Pfiffner, 2010). So an average erosion rate of 3.3 cm per year can be estimated.

The rock masses are mainly build-up out of limestone that slide downwards on a basal slip surface. The stated age was developed out of dC^{14}-dating of wood pieces found underneath the debris. The fact that the river flow was stopped first and started again with a flood, could be proven by anomalies in the sediments of the Lake Constance. In addition, horizons of bigger river pebbles could be correlated with ages to prove the results of the Lake Constance deposits. Harder to elaborate are the causes of such events. Some triggering mechanisms, like major earthquakes, can often be developed out of human memoranda (Pfiffner, 2010). In contrary, other triggers are harder to identify. For this reason, the origin of the Flims' landslide is still not known for sure.

IX. Example 2: Pizzo Cengalo Rock Fall

On the 27th of December 2011 a part of the Pizzo Cengalo breaks off and falls into the Val Bondasca. Around 3 Mio m³ were released and are now impressively covering the area of the valley (*Figure 5*). The moving mass generates vibrations comparable to a 2.7 Richter magnitude of an earthquake. On the fieldtrip it was

nicely seen during the ascent to the Refugio Sciora. According to the Museum in the Torte Belvedereo in Maloja, the rock fall was initiated by frost weathering of former cracks.

X. Example 3: Val Pola Landslide

Another example of a major Alpine land movement is the Val Pola landslide. It accounts as most destructive and costly natural disaster of Italy in the last two decades (Crosta et al., 2004). It took place on the 28th of July 1987: Triggered by heavy rain fall, a rock volume of about 40 km³ ran downslope into the Adda river valley. The mass ran up the opposing hill for approximately 300 m and split up in the river, 1 km up and 1.5 km down the stream (Crosta, 2004). As well as in our first example, the event displaced the water of the river and initiated a flood. The resulting wave was up to 95 m high and destroyed al villages at the riverside. During the prior 3 days, a 900-m-long fracture developed at the slope. Based on this the villages could have been evacuated before the landslide was finally initiated. The slide itself took about 5 minutes only (Crosta et al., 2004).

XI. Risk Assessment

Both examples illustrate how events are used for recent risk assessment as well. The best possible prevention results out of the understanding of former events and to evaluate modern processes out of it (Sartori et al., 2003). To do so, e.g. the Swiss government equipped drilled channels with measurement apertures to get data of rock movement and stresses. Another indicator for weak spots in the rock units can be represented by former alluvial fans. Some analyzed landslides show superposition of different events on



Figure 5*: Picture of the Pizzo Cengalo rock fall. View from the way to the Refugio Sciora in SW direction. Original position at the slope is marked red, the recent debris fan was generated as a consequence.*

top of each other (Varnes, 1984).

If areas with weaker slopes are known, stability can be increased by systematic forestation. A whole forest prevents the ground from sun and rain contact and can reduce the influences of cold temperatures as well. In addition, the evapotranspiration of the leaves helps to get rid of fallen rain and water. Another important factor is the closed root-system that directly increases the stability of the ground (Varnes, 1984). If the slopes are too steep for forestation or the areas are too small for a forest, rock barriers and nets can be installed.

In general, risk maps can be developed. Due to the fact that fractures are more persistent and often better developed in homogeneous and compact lithologies, they account as lithology with an increased risk of landslides (Sartori et al., 2003). In addition areas of high ground water flow represent areas of increased risk (Sartori et al., 2003).

As example for risk assessment development studies on the appearance of rock falls can account. E.g. those by Brunetti et al. (2009). The team collected 19 darasets of landlide volumes with an overall number of 4416 landslides. They elaborated that rock falls and their volume are power-law distributed to an average power of 1.3 (*Figure 6*).

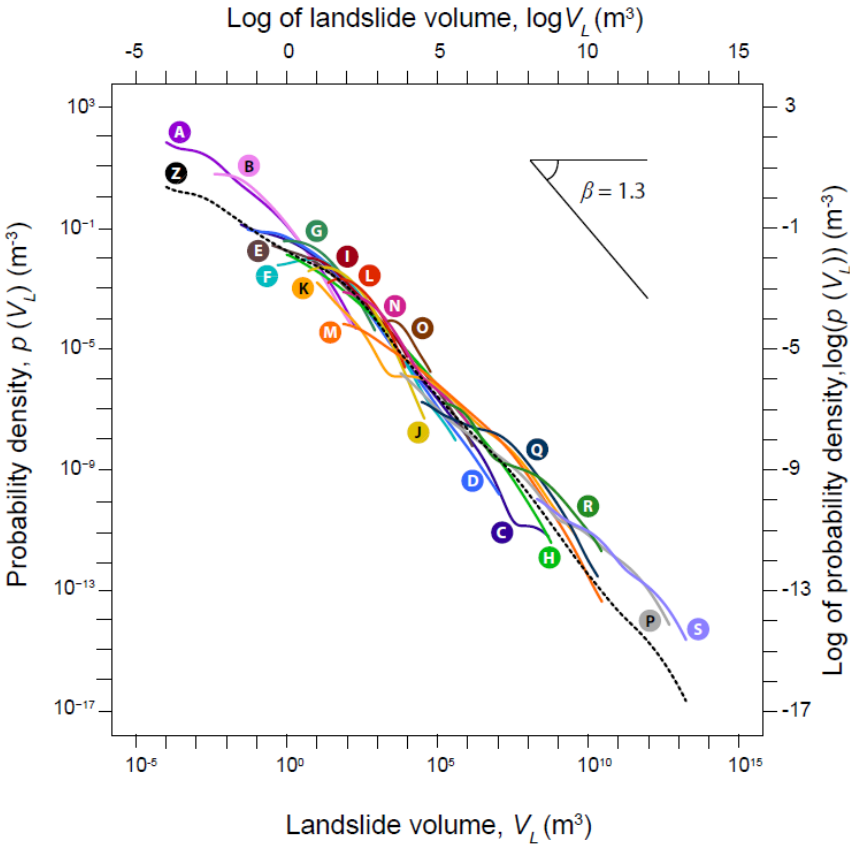


Figure 6: Probability density of landslide volumes as a function of the landslide volume. Plotted results show a power-law distribution to the power of 1.3. (Brunetti et al., 2009)

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