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Editorial

# Dating, triggering, modelling, and hazard assessment of large landslides

Large landslides, including rockslides, rock and debris avalanches, debris flows, and sackung (or slope sags), result from a complex of controlling features and processes (Hutchinson, 1988). Geological history (Ballantyne, 2002), lithology and structure (Zischinsky, 1966, 1969; Benko and Stead, 1998; Agliardi et al., 2001; Gutiérrez-Santolalla et al., 2005; Ambrosi and Crosta, 2006; Hermanns et al., 2006), slope relief and shape (Savage et al., 1985; Savage and Swolfs, 1986; Miller and Dunne, 1996; Martel, 2000; Molnar, 2004), weather and climate (Evans and Clague, 1994; Ballantyne et al., 1998; Ballantyne, 2002), seismicity (Solonenko, 1977; Radbruch-Hall, 1978; Keefer, 1984; Crosta et al., 2005; Chigira and Yagi, 2006; Hippolyte et al., 2006) and human activity (Heim, 1932; Cruden, 1976) are the most important causative factors.

Some of the above factors also control the geometry of the failure surface and its development both in space and time. A variety of data, models, and theories have been presented to explain the locations of large slope failures (Carrara, 1983), their geometry, time of occurrence, triggering mechanisms, rates and types of movement (Shreve, 1968; Melosh, 1979; Legros, 2002; Iverson, 2006; McSaveney and Davies, 2006), and their effects, including, for example, landslide damming, increased erosion, and impacts on structure. The associated risk can be high, both to communities and to critical infrastructure in hinterlands (Evans et al., 2006). The risk can extend far from the source slopes, for example due to landslide damming of rivers (Schuster, 2006) and generation of large water waves in lakes and reservoirs (e.g., Vajont, Italy in 1963; Hendron and Patton, 1985; see also examples in Voight, 1978).

This special issue of *Geomorphology* builds on a similar set of papers published in 2006 in *Engineering Geology* (volume 83, numbers 1–3). The focus of that issue was large landslides, but the papers covered a broad spectrum of subject matter. Similarly, for this special issue of *Geomorphology*, we have assembled a diverse set of papers, covering such subjects as triggers and causes of large landslides, chronology, modelling, and hazard and risk assessment. In our preface to the earlier *Engineering Geology* issue (Crosta and Clague, 2006), we listed some of the major aspects of large landslides that we considered to be understudied or controversial:

- Regional distribution within mountain ranges;
- triggers and causes, including the effects of climatic change;
- chronology, including initial movement, reactivation, and recurrence;
- failure mechanisms, including conditioning of the failure zone and final collapse;
- material behaviour, including internal deformation and transport mechanisms;
- style and degree of past and present activity;
- new tools for studying landslides and understanding their future evolution;
- passive vs. active controls exerted by geological structures;
- hydrological conditions;
- development of numerical models and codes for simulating triggering and movement, including rapid long runout;
- the role of humans in causing failure;
- quantitative assessment of hazard and risk; and
- appropriate remedial and mitigation measures.

These topics still require attention. In each case, progress is possible only by using a multidisciplinary approach involving fields such as geology, geomorphology, geochronology, engineering geology, hydrology, geochemistry, engineering, and geophysics. No single specialty applied alone will significantly advance our understanding of large landslides.

Some of the major topics listed above were addressed in the past issue. For example, Ambrosi and Crosta (2006), and Seno and Thuring (2006) documented the regional distribution of large sackung in the central Italian Alps, and Jarman reported similar features in Scotland (Jarman, 2006). Jibson et al. (2006) documented rock avalanches in Alaska triggered by a large earthquake in 2002. Geertsema et al. (2006a,b) and Weidinger (2006) described diverse landslides in, respectively, western Canada and the Himalaya. Several papers in the past issue dealt with constraints imposed on slope stability by different lithologies (Geertsema et al., 2006a,b; Mikos et al., 2006) geomorphology (Hermanns et al., 2006) and structure (Ambrosi and Crosta, 2006).

The papers in this issue differ in scope, type of phenomena, and methodological approach from those in the earlier volume, but they all address one or more of the topics listed above.

This issue comprises 13 papers, six dealing with the European Alps, two with the mountains of western North America, three with the Himalaya, and one with the mountains of Taiwan. One of the papers is on 3D physical modeling of large rock mass failures with no specific geographical reference. Ten papers focus on large rockslides and rock avalanches, one on earth-flows, two on sackung.

The chronological aspect, including initial movement, reactivation, and recurrence of large rock avalanches and sackung, is addressed in three papers (Agliardi et al., Ivy-Ochs et al., Prager et al.). This is still an important research subject to solve the major questions about the origin of these movements, the more influencing and controlling factors (e.g. glacial debuttressing , rock mass damage and weathering, groundwater changes, climatic changes, tectonic activity), their evolution (i.e. rapid or slow, or by successive pulses) and their present state of activity (especially for deep seated gravitational slope deformations).

The recognition of predisposing structural factors and of their role on failure and landslide type is considered in three other papers (Brideau et al., Dunning et al., Jaboyedoff et al.). Structural and tectonic features, rock mass properties, local morphology and slope aspect can


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interact to constrain slope failures. All these features can also be related to the mechanism of failure and to the possibility to generate slow or extremely rapid and catastrophic failures. Failure mechanisms and the evolution of slope failure can be studied by means of physical and numerical modeling. Both of them have the advantage to simulate the behavior and to study the evolution of slopes and rock masses under different loading conditions, and in presence of various morphologies and structural features. This subject is discussed in two papers (Bachman et al., Van den Ham et al.).

Rapid rock and debris avalanches, as well as debris flows, are characterized by peculiar behaviors influenced by geometry of the failure surface, topography, type of material and its water content. They can occur in different environments and during their motion they can entrain material in different ways (e.g. by accreting, mixing, generating plash zones and secondary phenomena, surges) and by different mechanisms (e.g. basal shearing, scouring, undrained loading and liquefaction, plowing or bulldozing). Entrainment of material covering the landslide path (e.g. glacier: Evans and Clague, 1988; saturated deposits: Sassa, 1988; McDougall and Hungr, 2005; Chen et al., 2006; Crosta et al., 2006) can increase the volume, modify the composition and the rheological properties of the moving mass, and enhance landslide mobility. The effects of movement on different materials (sediment, rock, and glacier ice) are discussed in four papers dealing with the Mount Blanc (Deline and Kirkbride), the Himalaya (Weidinger and Korup), and Flims (Ivy-Ochs et al., Poschinger and Kippel). Finally, one paper is devoted to landslide hazard modeling in Taiwan (Shou et al.).

The papers are ordered by subject. The first group of papers includes those concerned with initial slope failure, factors controlling failure, and the post-failure evolution of the slope. The second group of papers focuses on the application of dating methods to reconstruct the chronology of the failure. The third group includes papers that apply physical and numerical models to reconstruct landslides, and the fourth group deal with hazard and risk assessment.

Jaboyedoff et al. re-examine the 30 $Mm^3$ Frank rock avalanche, which occurred in 1903 at Turtle Mountain (Alberta, Canada) and claimed about 70 lives in the mining town of Frank. They examine the role played by structural discontinuities in the sedimentary rock mass of Turtle Mountain in causing the initial failure. Using a novel software tool, the authors identify joint and fault sets, compare and validate them with field measurements, and analyze the failure with the aid of a digital elevation model.

The paper by Dunning et al. presents data on landslides along the east–west transport corridor in the Himalaya of eastern Bhutan. They use a similar approach to that employed by Jaboyedoff et al. at Turtle Mountain, extracting structural information from photographs of failed slopes using a laser scanner. They define the geometry of selected landslides, discontinuity attitudes, failure surface characteristics, and the mode of failure. Based on this analysis, they propose a hierarchical classification of landslides, showing how different types of instability are nested within valley-scale deformation and discussing the links between them.

Brideau et al. illustrate the importance of tectonic structures and associated rock-mass discontinuities on catastrophic slope failure, using the Hope Slide (British Columbia, Canada, 1965) and the Randa rockslide (Switzerland, 1991) as examples. They employ engineering geological mapping, laboratory testing, GIS data analysis, and preliminary numerical modelling to show that specific failure mechanisms may be related to rock-mass strength, which they quantify using a Geological Strength Index (GSI) classification.

Poschinger and Kippel discuss the origin of unusual alluvial deposits near the margin of the Holocene Flims rockslide. The Bonaduz gravel deposit has an internal structure indicative of transport in a debris stream of about 100 $Mm^3$. The authors suggest that the alluvium was liquefied and mobilised by the impact of the rockslide on the valley floor.

Weidinger and Korup present sedimentologic and lithologic field evidence for the detachment and deposition of an enormous (about $2.5\times10^9$ $m^3$) rockslide in the Himalaya near Kanchenjunga (8585 m asl). Transported leucogranite and migmatite debris, derived from rocks 8 km upvalley, overlies in situ augen gneiss. The two units are separated by a micro-breccia that delineates a sliding surface across which the landslide travelled at high velocities. The presence of “frictionite,” or hyalo-mylonite, in samples of the micro-breccia indicates that a temperature of about 600 °C was achieved briefly as the debris moved along the 12° sliding plane. The authors suggest that the landslide was triggered by earthquake shaking.

Glacier regimen can be affected by deposition of rockslide or rock avalanche debris on the glacier surface. The debris, in turn, is substantially modified by glacier movement and melting in the months and years following the landslide. Hewitt describes these effects based on his observations after large rock avalanches at Bualtar Glacier in the Karakoram Himalaya in 1986. The glacier surged after the landslide and meltwater was ponded, leading to small outburst floods. By 2005, the landslide deposit had moved 9 km downglacier and had been so extensively reworked that it could no longer be distinguished from supraglacial debris produced by recurrent rockfall. Hewitt uses the phrase “disturbance regime” to describe landscapes that are perturbed by episodic catastrophic rock slope failures. These landscapes arise from adjustments among different process systems as a consequence of recurrent landsliding.

Deline and Kirkbride re-examine the timing and mode of emplacement of 1717 Val Ferret rock avalanche deposit in Italy. They offer a new geomorphic interpretation of the landslide deposits and provide relative and absolute dating showing that the 1717 deposit is smaller than previously thought. The 1717 deposit, and that of an earlier rock avalanche (pre-AD 1000) affected the regime of Triolet Glacier, causing it to advance and construct moraines that have no climatic significance.

Dating of two large rock-slides/avalanches from the Alps is the subject of two papers. The Fernpass rockslide deposit (Northern Calcareous Alps, Tyrol, Austria), was dated absolutely for the first time by using three independent radiometric dating methods ($^{14}C$, $^{36}Cl$, $^{230}Th/^{234}U$) by Prager et al.

Rockslide-dammed torrent deposits dated by $^{14}C$ indicate a minimum age of 3380–3080 cal. yrs BP; cosmogenic radionuclide $^{36}Cl$ ages of sliding planes have an arithmetic mean of 4100 ± 1300 yrs; post-depositional carbonate cements, which locally lithified the rockslide debris, yielded a $^{230}Th/^{234}U$ minimum age of about 4150 ± 100 yrs. All dating data indicate a Subboreal age and a primary rockslide morphology not shaped by late-glacial ice.

Ivy-Ochs et al. dated the Flims rockslide (8–12 $km^3$) in Switzerland. The $^{36}Cl$ corrected exposure ages from boulders and bedrock range from 5340 ± 490 yr to 15,440 ± 1480 yr. Ages for deglaciation of Segnes Valley (11,410 ± 590 yr and 13,340 ± 1090 yr) were obtained on bedrock surfaces outside of the landslide zone. The average of seven boulder ages on the landslide is 8900 ± 700 years, which agrees with published radiocarbon ages. As a consequence, the Flims, Köfels (9800 yr) and Kandertal (9600 yr) occurred during the transition to warm wet conditions during the early Holocene.

The Mt Watles complex deep-seated gravitational slope deformations (DSGSD), extending 20 km along upper Venosta Valley (eastern Alps, Italy), is studied by Agliardi et al. This is one of a series of DSGSDs recognized by the authors in the valley and currently being studied. Mt Watles exhibits spectacular DSGSD features and it occurs along a nappe boundary corresponding to a major tectonic element (Schlinig normal fault) in an area conditioned by recent faults marked by shallow earthquakes, and glacial/paraglacial evolution. This study indicates the importance of the Schlinig fault and recent fracturing on slope failure but also that the trigger seems to be associated to postglacial debuttressing. Radiocarbon dating of peat deposits (oldest dating available in the Italian central Alps) indicates that slope deformation started during the Lateglacial period and continued during the Holocene in several slope sectors.

3-D physical modelling and 2-D numerical modelling were used by Bachmann et al. to analyze the development of DSGSD. Physical modelling was performed by using scaled analogue materials and an original vertical accelerator device. This device allows to follow the evolution of the deformation process by cyclic loading of the model and so is well suited to analyze rupture initiation and evolution. Unilateral and bilateral failures of mountain ridges are described together with a series of other secondary fractures. The authors also try to simulate numerically their experiments. The numerical results reproduce relatively well failure initiation, but poorly the large deformation.

Van dem Ham et al. simulate a large-size creeping slope, from the upper Austrian Alps, by the finite element (FE) method, adopting a visco-hypoplastic material model. This model allows the description of the mechanical behaviour of cohesive soils with viscous effects. Material parameters were determined by means of geotechnical tests using representative soil samples taken from the slope. The computed slope movements are compared with inclinometer measurements available for a period of 16 years.

Coupling of limit equilibrium analyses, Monte Carlo approach and Geographic Information System (GIS) has been implemented by Shou et al. to evaluate landslide hazard including the effects of spatial uncertainties. The 3-D surface geometry, material distribution and groundwater level are processed for slope stability analysis using a GIS considering them as random variables. This approach was applied to the Li-shan landslide in Central Taiwan.

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