Landslides and Engineered Slopes: Protecting Society through Improved Understanding – Eberhardt et al. (eds)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-62123-6

Historical evolution of multi-source mudslides

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ABSTRACT: Multi-source mudslides are among the main types of mass movements affecting the Daunia Apennines, in Apulia (SE Italy). Threatening many towns, as well as communication routes and lifelines, they represent one of the most significant natural hazard in this area, with seasonal reactivations triggered by heavy rainfall. Complexity of the phenomena derives essentially from the existence of multiple source areas that can act as independent mass movements. Selected mudslides are analyzed in this paper through a multi-temporal analysis, based upon aerial photo interpretation of different years, integrated by field surveys in recent years. Production of landslide inventory map for each available set of air photos resulted in Landslide Activity Maps (LAMs) derived from a comparison of the individual inventory maps. LAMs provide useful insights into the evolution of the landslide processes, allowing us to reconstruct a relative history of the mass movements, and to highlight the most active sectors through time.

1 INTRODUCTION

The Daunia Apennines (Apulia, SE Italy) are intensely affected by land instability, with slope movements occurring on a seasonal basis, mainly related to rainfall triggering. At the same time, the effects of earthquakes and anthropogenic triggers cannot be ignored. The most typical typologies of instability phenomena in Daunia belong to the categories of shallow landslides (soil slips; Fig. 1) and to flow-type phenomena. This is due to the prevailing clay materials cropping out in the area, and to the generally low relief energy of the slopes.

Our interest in landslides in Daunia is focused on flow-type movements (Hungr et al., 2001) that frequently affect directly the outskirts of the towns and the main communication routes, locally causing serious problems in the transport of people and goods. Aimed at reconstructing the history and the recent evolution of the most typical slope movements in Daunia, and at correlating their occurrence to triggering factors, in this paper we deal with analysis of mudslides, defined as a complex phenomenon where significant internal distortion of the material occurs, but the dominant movement takes place along shear surfaces bounding the moving mass. When more than a single source area is present, we use the term multi-source mudslides. A mudslide often begins as a rotational or translational slide, including the aforementioned soil slips, whilst only in the post-failure stage the flow style is completely revealed, and the material keeps moving for long distances (Pellegrino et al., 2003). On a velocity scale (Cruden & Varnes 1996) mudslides are much lower than debris flows and flowslides, being generally characterized by slow velocity (1.6 m/year), occasionally reaching the moderate velocities (13 m/month) during main re-activations.

Figure 1. Soil slips in a clay slope in Daunia.

Multi-source mudslides are a type of mass movement which is particularly difficult to model and to control, due to a number of reasons. For example, multiple source areas can act as independent mass movements, so that at a given time one may be active, while others do not have any activity. At the same time, all source areas contribute to the overall movement, delivering material within the main channel, and feeding the whole landslide body. In order to attempt any mitigation measure, it is necessary to reach a full comprehension of the phenomenon, which can be obtained through a multi-temporal analysis, based upon aerial photo interpretation of different years, possibly integrated by field surveys. Production of landslide inventory map for each available set of air photos results in landslide activity maps (LAMs) derived from comparison of the individual inventory maps. LAMs provide useful insights into the evolution of the landslide process, allowing one to reconstruct a relative history of the mass movement, and to highlight the most active sectors through time. This result can be extremely useful to correlate likely movements to anthropogenic activity or specific triggering factors, such as seismic events or rainstorms.

In general, flow-type movements with slow to moderate velocity are particularly suitable for analysis of deformation features produced by the landslide activity. Active landslides (*sensu* WP/WLI 1993) are characterized by deformational features that are the result of differential movement within the mobile mass, and between it and the surrounding immobile material. The nature of the features, and their positions and orientations, are indicative of different kinds of deformation. Surface features are short-lived and can be continuously created and destroyed by the movement. Observation of their presence and distribution, and surveying of their evolution provide insights for the zonation of the mass movement in sectors characterized by different behavior (Fleming & Johnson 1989, Parise et al., 2003).

Identification of elements that characterize different parts of a landslide is an important aspect in the geomorphological analysis of mass movements. However, depending on factors such as type of landslide, rate of movement, and rheology of materials involved, some of these features persist, and their observation through time can be useful for understanding the kinematics of the landslide, evaluating the related hazard, and recognizing different phases in its history of movement. Among the many different types of features that can be observed at the surface of active mudslides, those located at the flanks (Fig. 2) can be particularly indicative for reconstruction of the geometry of slip surfaces and identification of the dominant type of movement occurring within the landslide mass (Hutchinson 1983, Carter & Bentley 1985, Cruden 1986, Parise 2003). In mudslides, the features located along the flanks often represent the surface expression of the shear planes bounding the landslide, and controlling its movement. Even though many features are ephemeral, due to weathering, erosion and ongoing deformation tending to erase prior traces of movements (Wieczorek 1984), their analysis can be extremely important for deciphering kinematics and movement history. This is in particular true for the direct indicators of deformation, i.e., those structures directly connected to structural discontinuities affecting the landslide material (IAEG Commission on Landslides 1990, Fleming & Johnson 1989).

Figure 2. Typical slickensided shear surfaces along a continuous levee bounding the moving mass in a mudslide.

2 GEOLOGICAL SETTING

The northern portion of the Apulia region represents a crucial area where the Southern Apennines thrust belt-foredeep-foreland system is visible in the field (Menardi Noguera & Rea 2000, Patacca & Scandone 2007). Unlike the adjacent Adriatic and Ionian areas, the Apennines underwent considerable uplift, weathering, and erosion, beginning in the middle Pleistocene (Doglioni et al., 1994). Three different sectors of the Apennine mountain belt can be distinguished (Fig. 3): the Daunia sector consists of a series of allocthonous tectonic sheets (Ligurid/Sicilid, Apenninic Platform and Lagonegro-Sannio units) mainly derived from the deformation of the Meso-Cenozoic Thetyan palaeo-domines during the Oligocene—Miocene Southern Apennine mountain building stage; the intermediate sector consists of poorly deformed Plio-Pleistocene marine to continental units filling the Bradanic foredeep; the more external (eastern) sector consists of a regularly bedded carbonate succession belonging to the Apulian foreland.

The front of the Southern Apennines thrust belt in Daunia is made by the superimposition of a series of tectonic units and by the related thrust deposits having the Cretaceous to lower Miocene basin argillaceous deposits (Varicoloured Clays) as

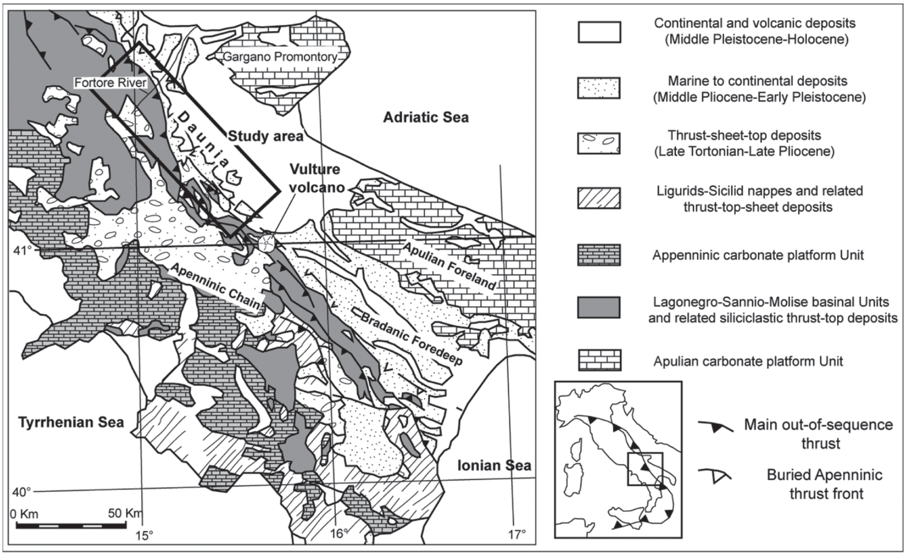

Figure 3. Sketch geology of the Southern Apennines of Italy. The black rectangle indicates the study area (Daunia Sub-Apennines).

a common base. Upward these tectonic nappes are covered by Miocene formations. Most of the landslides take place in the areas where the Miocene argillaceous deposits crop out. This is due essentially to: i) the frequent occurrence of thick clay intervals in the stratigraphic successions; and ii) the high degree of tectonic deformation in the outcropping rocks.

3 SLOPE MOVEMENTS

To better emphasize the main characters of multisource mudslides, two key areas, located near the towns of Alberona and Motta Montecorvino will be described in detail in this section. They are widely affected by compressive tectonics producing large-scale folding and thrusting. These characteristics, coupled with the lithology, represent an important factor favouring the development of widespread mass wasting. In addition to geological and morphological field surveys, and to multitemporal aerial photo interpretation, our studies included morphometric analysis for a complete description of the examined slope movements. The considered parameters are defined in Fig. 4, and listed in Table 1.

3.1 *Case study 1: Alberona*

Geologically, at Alberona, the varicoloured clays pass upward to quartz-rich sandstones, followed by some tens of meters-thick grey, locally

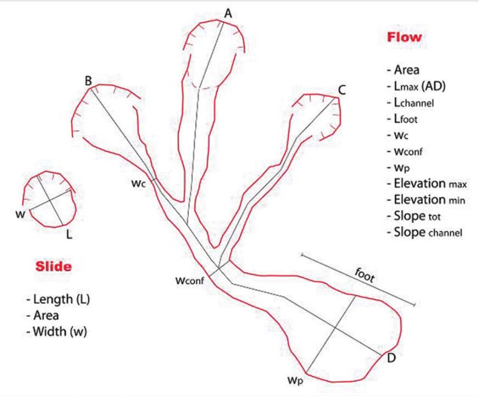

Figure 4. Sketch showing the morphometric parameters taken into account.

Table 1. Morphometric parameters of the two case studies (for explanation of the symbols see also Fig. 4).

	Alberona	Motta montecorvino
L_{max}	2510 m	3770 m
$L_{channel}$	1300 m	1360–1230 m
L_{foot}	910 m	450 m
$Slope_{tot}$	14%	11%
$Slope_{channel}$	9%	8–11%
W_{conf}	160 m	260 m
W_p	420 m	370 m
El_{max}	760 m a.s.l.	855 m a.s.l.
El_{min}	505 m a.s.l.	460 m a.s.l.

bentonite-rich, clays. The Alberona succession ends with a series of regularly bedded calcarenites and calcirudites.

The mudslide started from two source areas, both with initial rotational movement (Fig. 5). One of the source areas is entirely in the calcarenite-calcirudite sequence, whilst the other is at the contact between the calcareous sequence and the alternating sequence of clay-limestone (Fig. 6). After a track of a few hundred of meters, the material coming from the main source areas, plus further materials from lateral sources, reached the extremely narrow and long main channel. The overall morphology of the channel appears to be strongly controlled by the surrounding geomorphic situation: once the slope gradient decreases, the channel is unrestricted, and the moving mass spreads to create a lobate and wide foot, highlighted by a bulge, several meters high and over 900 m long. Further evidence of the widespread mass wasting in the area is highlighted by additional source areas feeding the landslide foot from the north (Fig. 6).

Figure 5. Crown area of one of the sources of the Alberona mudslide, showing a clear rotational character.

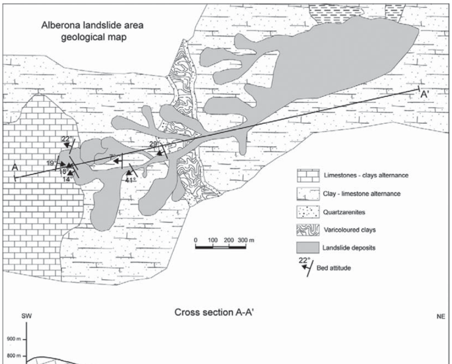

Figure 6. Geological map of the mudslide at Alberona.

Given the lower values in slope gradient, mudslides in these source areas start directly as flows, and do not show the rotational character of the higher source areas.

3.2 *Case study 2: Motta Montecorvino*

At Motta Montecorvino, the stratigraphy is essentially made by varicoloured clays passing upward to calcarenite and calcirudites, without the stratigraphic interposition of quartz-rich sandstones and clays. In addition, a very consistent clay interval has been recognized in the upper part of the succession. These stratigraphic lateral variations are very common in Daunia. The Motta Montecorvino mudslide is complex, showing two main source areas (in turn, each of these consists of several multiple sources, then feeding a channel), whose materials eventually converge to feed the landslide foot on the lower slope. Most of the source areas had rotational movement, being located in the part of the succession where carbonate deposits predominate. However, the interbedded clay materials (Fig. 7) provide large amount of silts and clays to the overall flow.

Unlike at Alberona, where a single channel collects the landslide material from several source areas, at Motta Montecorvino two channels can be identified (Fig. 7), which act independently along long tracks, and converge only near the footslope. Due to this peculiarity, the morphometric parameters regarding the channel in Table 1 show two separate values for the Motta Montecorvino mudslide: the first value refers to the western channel, and the second to the eastern one.

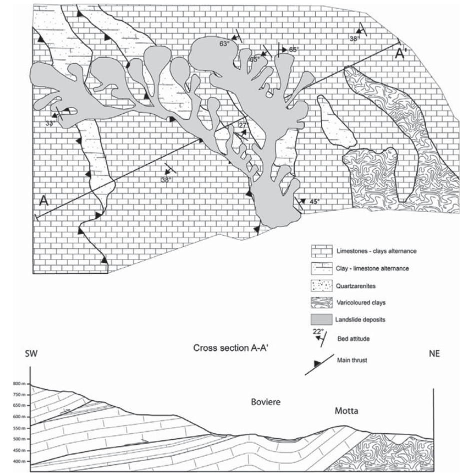

Figure 7. Geological map of the Motta Montecorvino mudslide.

4 MULTI-TEMPORAL ANALYSIS

The use of historical data in the analysis of natural hazard has long been recognized as a fundamental tool for hazard assessment (Varnes 1984). Historical data, as a matter of fact, may fill the need for knowledge about the temporal occurrence of the events, thus moving the assessment from susceptibility to hazard (Calcaterra & Parise 2001, Glade et al., 2001). Among the many possible sources of historical information, aerial photographs are very useful for reconstructing the recent evolution of the landscape. Multi-year analysis of aerial photos in particular, is a powerful and economical tool which only requires availability of photos from different flights and the work of an expert interpreter (Soeters & van Westen 1996, Parise 2001). Comparing several air photos allows a researcher to detect the recent evolution of natural phenomena, the land use changes in the considered time span, and the efficiency of remediation works installed to mitigate specific hazards (Parise & Wasowski 1999).

For the sake of brevity, we present the results of the multi-temporal aerial photo interpretation at the Alberona site. Four different sets of aerial photos have been used, covering the time span from 1954 to 2003 (Table 2). For each set of air photos, a landslide inventory map was produced that showed a distinction between active and dormant landslides, with additional morphological features such as areas of active erosion, active incision, etc. By integrating the information derived from such maps, the temporal evolution at the site may be portrayed (Fig. 8). In addition, field surveys in the years 2001–2011 integrated the results from aerial photo interpretation, supporting the interpretations with field-based geological and morphological observations.

Table 2. Date and average scale of aerial photograph sets used in the study.

Alberona		Motta montecorvino	
Date	Scale	Date	Scale
Sept. 13, 1954	1:35,000	Sept. 13, 1954	1:35,000
June 12, 1976	1:30,000	June 12, 1976	1:30,000
June 16, 1991	1:33,000	October 5, 1999	1:30,000
May 26, 2003	1:33,000	May 26, 2003	1:33,000

As in most of Daunia, and in large portions of the Southern Apennines of Italy, the 1954 air photos show intense mudslide activity at Alberona. Such activity was the effect of several seasons of intense precipitation that caused widespread slope instability especially in sectors underlain by clay deposits. The 1954 landslide inventory map shows that the active mudslide is fed by two main source areas, but also receives additional material from lateral, minor sources. All the material moved in the main, very narrow, channel and created a wide foot on the lower slope. It is worth noting that the landslide foot covers a wider foot morphology which is evidence of a palaeo-landslide. Many slopes in Daunia have this situation, and at several sites it is possible to identify large source areas of complex landslides, whose deposits have been preserved only partially because fluvial erosion has removed them from the areas of original accumulation. Nevertheless, identification of such ancient features represents the main evidence of the long-history instability of slopes in Daunia.

In the decades following the 1950s, the rate of activity generally decreased, as shown by analysis of both the 1976 and 1991 photos. In these decades, the landforms related to gravitational processes became progressively more subdued (Fig. 8): in 1976 the main body of the landslide, including its foot, are still clearly identifiable, whilst 15 years

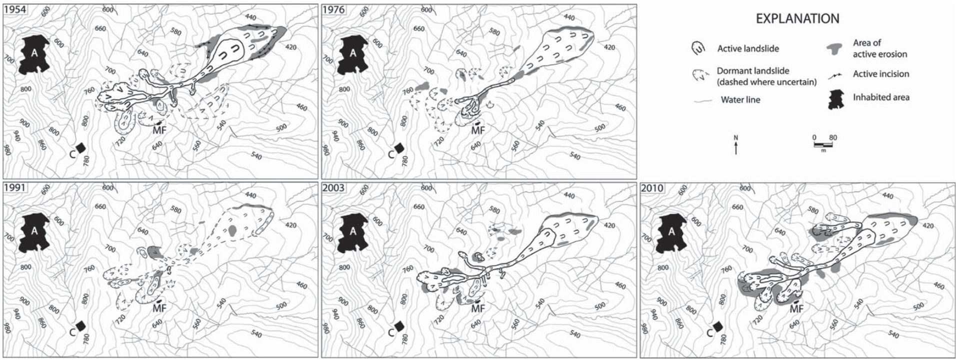

Figure 8. Landslide activity maps of the mudslide at Alberona (time span 1954–2010). Lettering indicates the localities cited in the text: A = Alberona, C = cemetery, MF = Masseria Frazzana.

later their evidence is not so neat, with most of the recognized features drawn as uncertain (dashed lines in Fig. 8). It has to be noted, however, that no significant changes in the land use occurred in the area in the considered time span. Thus, it seems that the differences observed through time in the landslide features are simply related to a decreasing stage in the evolution of the slope movement.

Starting in 2001, however, a new phase of intense activity began, which is highlighted by the 2003 air photos, taken few months after an intense rainstorm which occurred in late January 2003 (Parise 2005). In about 2001, two main source areas re-activated, feeding the main channel and giving new life to the overall movement. Many of the ancient lateral sources were also re-activated, and this trend continued into recent years, as shown by the 2010 map (Fig. 8), that has been produced by field surveys. The most significant rainfall events, that generally are concentrated in the study area in the winter-early spring period, have been in recent years the main trigger for re-activating the mapped landslides. Beside the active landslide mapped in the 2010 map, the high percentage of active erosional areas shown will likely lead to future enlargement of the overall movement.

5 CONCLUSIONS

Multi-source mudslides are the most common type of mass movement in Daunia, causing severe problems to many communication routes and lifelines in the area, and locally affecting the outskirts of towns. Given the complexity of the phenomena, characterized by multiple source areas, any mitigation measure attempted must take into account the nature of the phenomenon. This can be obtained through a multi-temporal analysis, based upon aerial photo interpretation of different years, and integrated by field surveys. At this latter regard, identification of the elements that characterize different parts of a landslide represents an essential aspect in the geomorphological analysis of mass movements. In the case studies described in this article, very clear and long shear surfaces have been recognized in the field along the flanks of the moving mass, as the most striking features produced by the movement. Recognition and mapping of these features greatly helped in the production of the landslide inventory maps shown in Figure 8, in the reconstruction of the geometry of the slip surfaces, and in the identification of the dominant type of movement occurring within the landslide mass. In our case, all of this resulted in classifying the two case studies as mudslides, thus providing crucial information to be used for any future remediation measures.

Combined to the studies above recalled, the production of landslide activity maps described in this paper for the Alberona site points out a tool that can provide useful insights into the evolution and history of mudslides, and identify their most active sectors through time. These results may be extremely useful to correlate movements to anthropogenic activity or specific triggering factors, such as seismic events or rainstorms.

ACKNOWLEDGMENTS

This study was supported by funds from *Progetti di Ricerca di Interesse Nazionale* (PRIN) 2008, by the Italian Ministry of University and Scientific Research.

REFERENCES

Calcaterra, D. & Parise, M. 2001. The contribution of historical information in the assessment of the landslide hazard. In T. Glade, P. Albini & F. Frances (eds.), *The use of historical data in natural hazard assessment:* 201–217. Adv. in Nat. and Techn. Hazards Res. 17 Kluwer Acad. Publ.

Carter, M. & Bentley, S.P. 1985. The geometry of slip surfaces beneath landslides: prediction from surface measurements. *Can. Geotech. J.* 22: 234–238.

Cruden, D.M. 1986. The geometry of slip surfaces beneath landslides: prediction from surface measurements. Discussion. *Can. Geotech. J.* 23: 94.

Cruden, D.M. & Varnes, D.J. 1996. Landslide types and processes. In A.K. Turner & R.L. Schuster (eds.), *Landslides: Investigation and Mitigation*: 36–75. Transp. Res. Board Sp. Rep. 247, Nat. Acad. Press, WA.

Doglioni, C., Mongelli, F. & Pieri, P. 1994. The Puglia uplift (SE-Italy): an anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere. *Tectonics* 13 (5): 1309–1321.

Fleming, R.W. & Johnson, A.M. 1989. Structures associated with strike-slip faults that bound landslide elements. *Engineering Geology* 27: 39–114.

Glade, T., Albini, P. & Frances, F. (eds) 2001. *The use of historical data in natural hazard assessment.* Adv. in Nat. and Techn. Hazards Res. 17 Kluwer Acad. Publ.

Hungr, O. 2003. Flow slides and flows in granular soils. In L. Picarelli (ed.), *Proc. Int. Workshop "Occurrence and mechanisms of flow-like landslides in natural slopes and earthfills"*: 37–44. Patron, Bologna.

Hungr, O., Evans, S.G., Bovis, M. & Hutchinson, J.N. 2001. Review of the classification of landslides of the flow type. *Environmental and Engineering Geoscience* 7: 221–238.

Hutchinson, J.N. 1983. Methods of locating slip surfaces in landslides. *Bull. Ass. Eng. Geologists* 20 (3): 235–252.

IAEG Commission on Landslides 1990. Suggested nomenclature for landslides. *Bull. Int. Ass. Eng. Geology* 41: 13–16.

Menardi Noguera, A. & Rea, G. 2000. Deep structure of the Campanian-Lucanian Arc (Southern Apennine, Italy). *Tectonophysics* 324: 239–265.

Parise M. 2001. Landslide mapping techniques and their use in the assessment of the landslide hazard. *Journal of Physics and Chemistry of the Earth, part C* 26/9: 697–703.

Parise, M. 2003. Observation of surface features on an active landslide, and implications for understanding its history of movement. *Nat. Hazards Earth System Sc.* 3 (6): 569–580.

Parise, M. 2005. Landslide-controlled geomorphological evolution in clayey slopes of southern Italy. *Proc. 6th Int. Conf. on Geomorphology, Zaragoza,* abstr. vol.: 167.

Parise, M. & Wasowski, J. 1999. Landslide activity maps for the evaluation of landslide hazard: three case studies from Southern Italy. *Natural Hazards* 20 (2/3): 159–183.

Parise, M., Coe, J.A., Savage, W.Z. & Varnes, D.J. 2003. The Slumgullion landslide (southwestern Colorado, USA): investigation and monitoring. In L. Picarelli (ed.), *Proc. Int. W. "Occurrence and mechanisms of flow-like landslides in natural slopes and earthfills"*: 253–263. Patron, Bologna.

Patacca, E. & Scandone, P. 2007. Geology of the Southern Apennines. *Boll. Soc. Geol. It.,* Spec. Issue 7: 75–119.

Pellegrino, A., Picarelli, L. & Urciuoli, G. 2003. Experiences of mudslides in Italy. In L. Picarelli (ed.), *Proc. Int. Workshop "Occurrence and mechanisms of flow-like landslides in natural slopes and earthfills"*: 191–206. Patron, Bologna.

Soeters, R. & van Westen, C.J. 1996. Slope instability recognition, analysis, and zonation. In A.K. Turner & R.L. Schuster (eds.), *Landslides: Investigation and Mitigation*: 129–177. Transp. Res. Board Sp. Rep. 247, Nat. Acad. Press, WA.

Varnes, D.J. 1984. Landslide hazard zonation: a review of principles and practice. Unesco Press, Paris.

Wieczorek, G.F. 1984. Preparing a detailed landslide-inventory map for hazard evaluation and reduction. *Bull. Ass. Eng. Geologists* 21 (3): 337–342.

WP/WLI (Working Party on World Landslide Inventory) 1993. A suggested method for describing the activity of a landslide. *Bull. Int. Ass. Eng. Geology* 47: 53–57.