Available online at www.sciencedirect.com
ScienceDirect
Earth-Science Reviews 87 (2008) 1 – 38
EARTH-SCIENCE REVIEWS
www.elsevier.com/locate/earscirev

Legacies of catastrophic rock slope failures in mountain landscapes

Kenneth Hewitt [a,1], John J. Clague [b,*], John F. Orwin [c,2]

[a] *Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, Ontario N2L 3C5, Canada*
[b] *Centre for Natural Hazard Research, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
[c] *Department of Geography, University of Otago, PO Box 56, Dunedin, New Zealand*

Received 27 March 2007; accepted 17 October 2007
Available online 6 November 2007

Abstract

This review examines interpretive issues relating to catastrophic, long-runout landslides in the context of large numbers of recently discovered late Quaternary events. It links relevant research in landslide science, including some novel or hitherto-ignored complexities in the nature and role of these events, to broader concerns of mountain geomorphology. Attention is drawn to mountain ranges known to have large concentrations of events. In particular, discoveries in three regions are singled out; the Karakoram Himalaya, the coastal mountains of northwestern North America, and the Southern Alps of New Zealand. In each region, many new events, or previously unrecognized complexities, have been identified in the past decade or two. Research on the sedimentology and geomorphology of prehistoric, eroded deposits has been critical to identifying rock avalanches, including many that were formerly attributed to other processes. Discoveries of rock avalanches in the ancient stratigraphic record have helped with the field recognition of rock-avalanche materials and in developing facies models of deposits with complex emplacement histories. The stratigraphic record also provides insights into interactions of streaming rock debris with deformable substrates. Such interactions are responsible for "landslide-tectonized" forms and transformation of rock avalanches into debris flows. Of special interest are runout geometries involving the interactions of rock avalanches with topography or substrate materials, and travel over glaciers. Other emerging issues relate to reconstruction of detachment-zone geometries, and slow, deep-seated slope movements that may trigger catastrophic failure. Most previous landslide studies have focused on individual events or general models, whereas the questions addressed here arise from a comparative approach emphasizing common and contrasting features among events in sets and in different regions. The scale and frequency of landslides in the regions of interest mean they have an important role in denudation, regional landform development, watershed evolution, and Quaternary environmental change. A major developmental factor, largely neglected, is persistent disturbance of high mountain fluvial systems by many successive landslides. Damming of streams and subsequent breaching of landslide barriers strongly influence inter-montane sedimentation and denudation, with particular significance in post-, para-, and inter-glacial contexts. Although an individual landslide appears as a "catastrophe" lasting only a minute or two, its legacy can persist as a morphogenetic influence for millennia or tens of millennia through disturbance of other processes. The influence is permanently felt; in effect, multiple events make the event a "normal" one in regions such as the three considered here.

Keywords: landslide; rock slope failure; rock avalanche; sackung; landslide-fragmented; rivers; mountains; geohazards

1. Introduction

Hundreds of rock slope failures larger than one million cubic meters in volume have been identified in the past several decades, mainly in the world's Cenozoic mountain belts. They are particularly common in the Alpine–Himalayan and Inner Asian ranges, and in the mountains of the Circum-Pacific orogenic belt (Voight and Pariseau, 1978). Of particular interest from scientific and hazard perspectives are areas with large numbers of catastrophic, long-runout landslides (Table 1; Abele, 1974; Voight, 1978; Eisbacher, 1979; Whitehouse and Griffiths, 1983; Eisbacher and Clague, 1984; Cruden, 1985; Hewitt, 1988, 1998; Brabb and Harrod, 1989; Savigny and Clague, 1992; Strom, 1998; Hermanns and Strecker, 1999; Weidinger and Ibetsberger, 2000; Evans and DeGraff, 2002; Abdrakhmatov et al., 2004; Blikra et al., 2006).

* Corresponding author. Fax: +1 778 782 4924.
E-mail addresses: khewitt@wlu.ca (K. Hewitt), jclague@sfu.ca (J.J. Clague), jfo@geography.otago.ac.nz (J.F. Orwin).
[1] +1 519 725 1342.
[2] +64 3 479 8706.

0012-8252/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.earscirev.2007.10.002

Table 1
Preliminary inventory of known, large (>10^6 m^3) catastrophic rock avalanches in the mountain ranges of the world

Number of known events	Mountain region
>100	Alps, Switzerland and Austria (Heim, 1932, Abele, 1974, von Poschinger, 2002)
	Karakoram Himalaya (Hewitt, 2004)
	Caucasus Ranges, Armenia (Karakhany and Baghdassaryan, 2004)
	Andes, Argentina and Chile (Hermanns and Strecker, 1999, Fauque and Tschilinguirian, 2002, Hauser, 2002)
	Southern Alps, New Zealand (Whitehouse, 1983)
51–100	Alaska-Yukon (Voight, 1978)
	China (Li, 2004, Weidinger, 2004)
	Pamir Ranges, Tajikistan (Schneider, 2004, Vinninchenko, 2004)
	Nanga Parbat and adjacent western Himalaya (Shroder, 1993, Hewitt unpublished field surveys)
10–50	Norway (Braathen et al., 2004, Blikra et al., 2006)
	Tien Shan Ranges, Kyrgyz Republic (Abdrakhmatov et al., 2004)
	Alps, Italy (Eisbacher and Clague, 1984)
	Northern Appenines (Abdrakhmatov et al., 2004)
	Hindu Raj-Hindu Kush, Pakistan (Shroder, 1993, Hewitt, 2001)
	Kun Lun, China-Tibet (Fort and Peulvast, 1995)
	Kazakhstan (Abdrakhmatov et al., 2004)
	Southern Tien Shan, Tajikistan (Vinninchenko, 2004)
	Gissar-Alai Range, Tajikistan (Vinninchenko, 2004)
	Nepal Himalaya (Fort and Peulvast, 1995, Weidinger, 2004)
	Taiwan (Evans and DeGraff, 2002)
	Rocky Mountains, Canada (Cruden, 1985, Jackson, 2002)
	Rocky Mountains, U.S. (Brabb and Harrod, 1989)
	Coast Mountains, British Columbia (Eisbacher and Clague, 1984)
	Mackenzie Mountains, NW Canada (Eisbacher, 1979)
	Coastal mountains, Washington, USA (Fahnestock, 1978)
	Sierra Nevada, USA (Wieczorek, 2002)

"Known events" may represent only a fraction of all rock avalanches, with the possible exception of those in Europe, Japan, and the Rocky Mountains.

In this review, we highlight major emerging issues in the study of catastrophic rock slope failures. We emphasize failure, transport, and depositional mechanisms, and the use of the depositional record to interpret the role of these events in the evolution of mountain landscapes.

We draw mainly upon our knowledge of three of the most impressive orogens on Earth, the Karakoram Himalaya of Asia, the high mountains along the coast of northwestern North America (the St. Elias and Coast Mountains), and the Southern Alps of New Zealand (Fig. 1a–c). The Karakoram and the St. Elias Mountains have some of the greatest relief on earth. Slopes commonly rise more than 3000 m, and in places as much as 6000 m, from valley bottoms to adjacent ridge crests and peaks. The Karakoram Himalaya has been described as the highest and steepest terrain on Earth (Miller, 1984), and parts of the St. Elias Mountains equal it in relief and grandeur. At first glance, the Coast Mountains of British Columbia and the Southern Alps of New Zealand are less impressive, as the elevations of Mt. Waddington and Aoraki/Mount Cook, the highest peaks in these ranges, are only 4019 m and 3754 m, respectively. This impression, however, is misleading; local relief in the Southern Alps, for example, exceeds 3000 m where the west side of the range rises abruptly from a narrow, flat coastal plain. This abrupt topographic change demarcates the Alpine Fault, the boundary between the Pacific and Australian plates. Given their relief, it is not surprising that the Karakoram, St. Elias Mountains, and Southern Alps have some of the highest rates of tectonic uplift on Earth (Searle, 1991). The higher watersheds are snowbound most or all of the year, and high valleys in the Karakoram and St. Elias Mountains contain the largest concentrations of glaciers outside Greenland and Antarctica (Hewitt et al., 1989). Most of the Karakoram and the Southern Alps, and the entire St. Elias and Coast Mountains, were glaciated during the Pleistocene, and valleys in these ranges have been steepened and deepened by ice. These regions have also experienced significant glacier thinning and retreat over the last century, debuttressing the toes of steep rock walls. This glacial legacy, coupled with the ability of some rocks to stand in steep slopes 1000–4000 m high, frequent strong earthquakes, ongoing tectonic deformation, and orographically enhanced precipitation, favor slope failures of unequalled size and impact. Not until the late 1970s and early 1980s, however, were more than a handful of these large landslides recognized in the Southern Alps (Whitehouse, 1983), the St. Elias Mountains (Rampton, 1981), and the Coast Mountains, and not until the 1990s were they identified in the Karakoram (Hewitt, 1999).

To date, 272 late Quaternary rockslide — rock-avalanche events have been identified in the Trans Himalayan Indus valleys of the Karakoram, Hindu Raj, and Nanga Parbat, mostly from the deposits they have left. Hundreds more remain to be discovered. The events include some of the largest landslides on Earth. Many exceed 100×10^6 m^3, and at least six are larger than 1000×10^6 m^3 (Table 2). Vertical displacements, from the top of the detachment zone to the runout limit, are at least 1000 m and in some cases more than 2000 m. Maximum horizontal displacements generally exceed 5 km, in some cases more than 12 km (Hewitt, 1998, 1999, 2001, 2004).