Reports

Rock Avalanches Caused by Earthquakes: Source Characteristics

Abstract. *Study of a worldwide sample of historical earthquakes showed that slopes most susceptible to catastrophic rock avalanches were higher than 150 meters and steeper than 25 degrees. The slopes were undercut by fluvial or glacial erosion, were composed of intensely fractured rock, and exhibited at least one other indicator of low strength or potential instability.*

Rock avalanches are among the most dangerous landslides triggered by seismic events; with the possible exception of rapid flows in unconsolidated soil, they have killed more people than any other type of landslide in recent earthquakes (*1*). One rock avalanche, dislodged from Nevados Huascarán, Peru, by an earthquake on 31 May 1970, killed at least 18,000 people (*2*) and was probably the most destructive landslide of this century.

In rock avalanches relatively coherent rock masses fall or slide from steep, high slopes and then disintegrate into streams of fragments that commonly entrain water, glacial ice, and unconsolidated soil material (*3*). The destructive power of these avalanches derives from their large volume (> 0.5×10^6 m^3) and their ability to transport material thousands of meters at velocities of tens or hundreds of kilometers per hour on slopes as gentle as a few degrees.

In this report criteria are presented for recognizing potential sources of earthquake-induced rock avalanches. The criteria were developed as a result of studying a worldwide sample of rock avalanches triggered by historical earthquakes (*4*). Data on height, inclination, and type of slope on which the rock avalanches originated were available for 50 avalanches, and descriptions of geological conditions were available for 27.

Figure 1A shows slope data for the 50 rock avalanches. Slope parameters are defined in Fig. 1B. The kinetic energy necessary for long-distance transport of rock avalanche material comes from the initial fall from the source, and Fig. 1A shows that only slopes higher than 150 m and steeper than 25° produced rock avalanches. Above the minima of 150 m and 25°, cumulative frequency plots of the number of sources versus slope height and inclination show relatively uniform distributions to 1120 m and 55°, respectively; two source slopes were higher than 1120 m (1220 and 1330 m) and one was steeper than 55° (76°). The median slope height for the sources of the 50 rock avalanches was 500 m and the median inclination was 40°. A majority of the data plotted in Fig. 1A are for rock avalanches triggered by the Alaska earthquake of 28 March 1964, a well-documented event of very high magnitude that affected a large area of rugged alpine terrain. Median slope height and inclination for the 1964 Alaska rock avalanches were 510 m and 45°, in comparison with 340 m and 37° for the other rock avalanches.

All but one of the 50 rock avalanches originated on slopes undercut by active fluvial erosion or active, Holocene, or late Pleistocene glacial erosion (Fig. 1A). The single exception (data point *1* in Fig.

Table 1. Location, date, earthquake magnitude, and geological conditions relating to 27 rock avalanches.

Location	Date	Magnitude*	Geological condition of source slope: Intense fracturing	Significant weathering	Planes of weakness dipping out of slope	Weak cementation	Previous slides†	Reference
1. Deer Creek, Santa Cruz Mountains, California	18 Apr. 1906	7.9	No	No	No	Yes	No	(*7*)
2. Khait, Soviet Union	10 July 1949	7.6	Yes	No	No	No	Yes	(*8*)
3. Lituya Bay, Alaska	10 July 1958	7.7	Yes	No	No	No	Yes	(*9*)
4. Madison Canyon, Montana	18 Aug. 1959	7.1‡	Yes	Yes	Yes	No	Yes	(*10*)
5. Puget Peak, Alaska	28 Mar. 1964	9.2	Yes	Yes	Yes	No	Yes	(*11*)
6. Shattered Peak, Alaska (west face)	28 Mar. 1964	9.2	Yes	No	Yes	No	No	(*12*)
7. Shattered Peak, Alaska (north face)	28 Mar. 1964	9.2	Yes	No	Yes	No	No	(*12*)
8. Shattered Peak, Alaska (south face)	28 Mar. 1964	9.2	Yes	No	No	No	No	(*12*)
9. Pyramid Peak, Alaska	28 Mar. 1964	9.2	Yes	No	Yes	No	No	(*12*)
10.–19. Bering–Martins River area, Alaska (ten rock avalanches)	28 Mar. 1964	9.2	Yes	No	No	No	No	(*6*)
20. Buller River Canyon, New Zealand	23 May 1968	7.1	No	Yes	No	No	No	(*13*)
21. Nevados Huascarán, Peru	31 May 1970	7.9	Yes	No	No	No	Yes	(*2, 14*)
22. Los Chocoyos, Guatemala	4 Feb. 1976	7.5	No	No	Yes	Yes	No	(*15*)
23. Estancia de la Virgin, Guatemala	4 Feb. 1976	7.5	Yes	Yes	No	No	Yes	(*15*)
24. San Jose Poaquil, Guatemala	4 Feb. 1976	7.5	Yes	No	Yes	Yes	No	(*15*)
25. Rio Teocinte, Guatemala	4 Feb. 1976	7.5	Yes	No	No	No	No	(*15*)
26.–27. Mount Baldwin, Sierra Nevada, California (two rock avalanches)	25 May 1980	6.1	Yes	Yes	No	No	No	(*16*)

*Magnitudes ≤ 7.6 are Richter surface wave magnitudes; magnitudes > 7.6 are moment magnitudes. †Incipient slope movement, historical landslides, or prehistoric landslide deposits in or near the source area. ‡Method of magnitude determination not reported.

1A) originated on a slope that was probably undercut by fluvial erosion at some time in the past. All but one of the reported rock avalanches from the 1964 Alaska earthquake originated on slopes above active glaciers (*5*). In the other earthquakes, rock avalanche sources were distributed approximately evenly among slopes undercut by active fluvial, active glacial, and Holocene or late Pleistocene glacial erosion.

Five common factors indicating a potential for rock avalanche generation are identified from descriptions of geological conditions in the 27 rock avalanche sources (Table 1). The most common factor was intense fracturing, which suggests that the source rock was broken by several intersecting sets of fractures spaced a few centimeters or decimeters apart. Other factors indicating rock avalanche potential were conspicuous planes of weakness (faults, bedding planes, or foliation surfaces) dipping out of a slope, weathering, weak cementation, and evidence of previous slope movement. Each source for which geological data were available exhibited at least one of these five factors; many sources exhibited two or more, a condition that appears to increase the likelihood of rock avalanche occurrence (*6*).

Thus, slopes most likely to produce rock avalanches during earthquakes are (i) steeper than 25° and higher than 150 m, (ii) undercut by active fluvial erosion or active or geologically recent glacial erosion, (iii) composed of intensely fractured rocks, and (iv) characterized by at least one other geological indicator of instability. Slopes that meet criteria (i) and (ii) and either criterion (iii) or (iv) have a lesser but still significant likelihood of producing rock avalanches; slopes not meeting these criteria are unlikely to produce rock avalanches during earthquakes. Although these criteria identify slopes that may produce rock avalanches, only a small fraction of those slopes will generate rock avalanches in a given earthquake. More detailed, site-specific geological and engineering studies are needed to determine the level of risk in a particular area.

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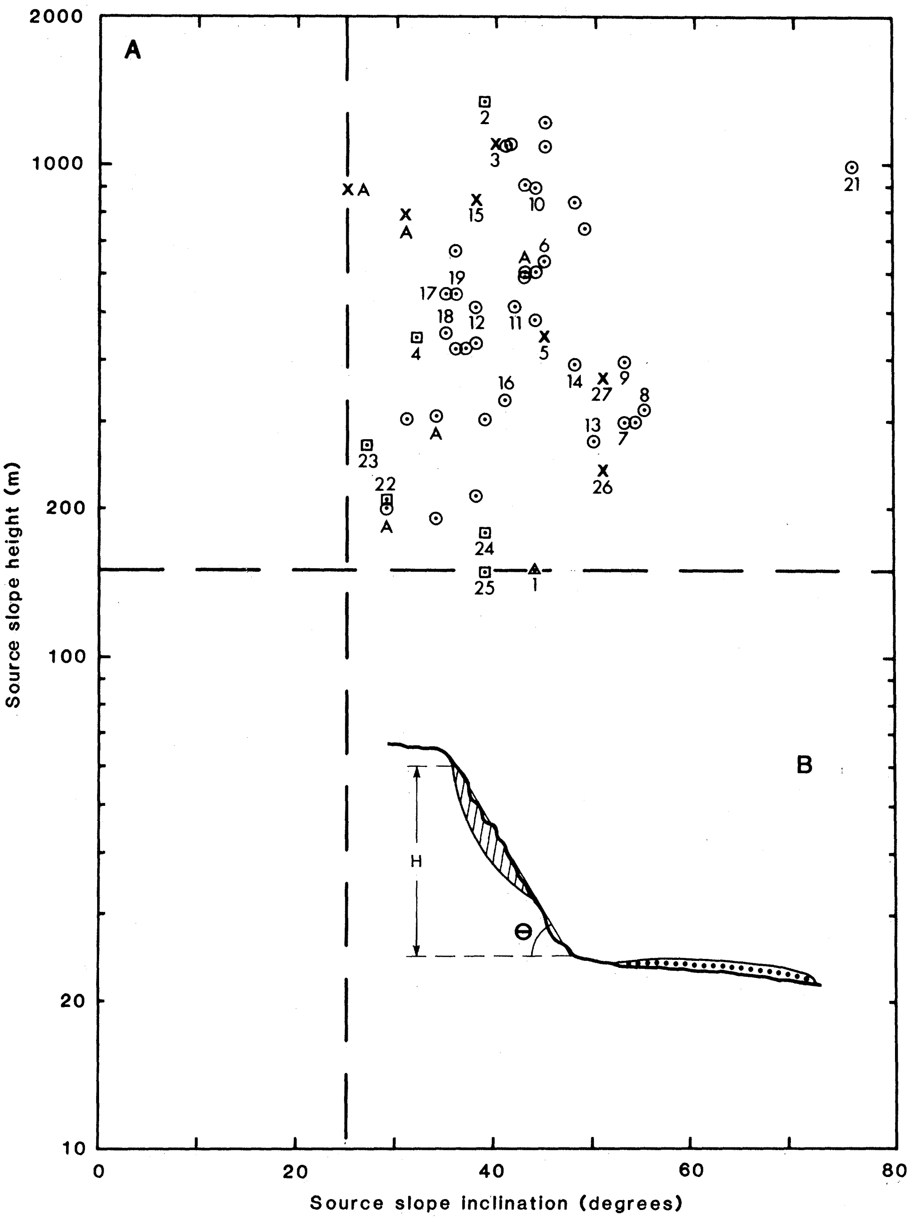

Fig. 1 (A) Heights and inclinations of source slopes of earthquake-induced rock avalanches. Height and inclination are defined in the legend to (B). Circles represent slopes undercut by active glacial erosion; squares, slopes undercut by active fluvial erosion; crosses, slopes undercut by Holocene or late Pleistocene glacial erosion; and the triangle, a slope not presently undercut by fluvial or glacial erosion. Source slopes are numbered as in Table 1. Points marked *A* represent source slopes of rock avalanches triggered by the Alaska earthquake of 10 July 1958; points with no number or letter represent source slopes of rock avalanches triggered by the Alaska earthquake of 28 March 1964. Minimum slope height, 150 m; minimum inclination, 25°. (B) Profile of idealized source slope and rock avalanche path. Hachured area shows the original position of the rock avalanche body; stippled area, the final position of the deposit. Source slope height *H* is the elevation difference between the highest point on the scarp and the base of the steep slope. Inclination Θ is the average inclination of this slope.

References and Notes

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2. G. Plafker, G. E. Ericksen, J. Fernández Concha, *Seismol. Soc. Am. Bull.* **61**, 543 (1971).
3. Landslides classified herein as rock avalanches include both "rock-fall avalanches" and "rock fall–debris flows" [D. J. Varnes, in *Landslides: Analysis and Control*, R. L. Schuster and R. J. Krizek, Eds. (Special Report 176, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1978), p. 11].
4. Studies described in (*1*) encompassed 40 relatively well documented earthquakes worldwide with magnitudes ≥ 5.2 and several hundred U.S. earthquakes with magnitudes ≥ 2.6 that were documented only by intensity data. Nine of the earthquakes, all with magnitudes > 6.0, caused a total of about 100 rock avalanches.
5. Source slopes above active glaciers are steeper and higher on average than other source slopes; this accounts for the greater median height and inclination of sources of the 1964 Alaska rock avalanches.
6. Sources of rock avalanches 10 to 19 in Table 1 were observed from a fixed-wing aircraft by A. Post [*U.S. Geol. Surv. Prof. Pap. 544-D* (1967)] and from some distance away on the ground by S. J. Tuthill and W. M. Laird [*U.S. Geol. Surv. Prof. Pap. 543-B* (1966)]. Other, undetected factors indicating rock avalanche potential could have been present in these sources. Of the other 17 sources listed in Table 1, 13 exhibited two or more geological indicators of rock avalanche potential.
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16. E. L. Harp and D. K. Keefer, unpublished data.
17. I thank N. E. Tannaci and D. H. Tuel for help in compiling data; E. L. Harp, R. L. Schuster, R. C. Wilson, A. M. Johnson, and G. W. Clough for thoughtful reviews; and T. L. Holzer for stimulating my interest in this topic.

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Biomass of Tropical Forests: A New Estimate Based on Forest Volumes

Abstract. *Recent assessments of areas of different tropical forest types and their corresponding stand volumes were used to calculate the biomass densities and total biomass of tropical forests. Total biomass was estimated at 205 × 10^9 tons, and weighted biomass densities for undisturbed closed and open broadleaf forests were 176 and 61 tons per hectare, respectively. These values are considerably lower than those previously reported and raise questions about the role of the terrestrial biota in the global carbon budget.*

The recent rise in atmospheric CO_2 concentration (*1*) due to the burning of fossil fuels and its potential effects on climate have renewed interest in the study of the global carbon cycle. Of particular interest is the attempt to balance the world's carbon budget and account for all known sinks and sources (*2*). At the present the budget appears to be unbalanced because of a proposed source of CO_2 from the terrestrial biota, estimated by Houghton *et al.* (*3*) as per 1.8×10^9 to 4.7×10^9 tons of carbon per year for 1980. Most of this proposed net flux from the biota (~ 80 percent) is due to changes in land use in the tropics.

The uncertainty in the magnitude of the flux due to tropical deforestation results partly from uncertainty in the estimates of the biomass density (or organic carbon density, as mass per unit area) of tropical forests and the rate of deforestation. The carbon densities of tropical forests commonly used in models of the terrestrial biota (*3, 4*) are those of Whittaker and Likens (*5*) and of our earlier study (*6*). Whittaker and Likens' study recognized two forest types with carbon densities of 160 to 200 ton/ha, giving a total carbon pool of 460×10^9 tons (or a weighted carbon density of about 188 ton/ha). In our study, we recognized six forest types with carbon densities of 40 to 185 ton/ha, giving a total carbon pool in tropical forests of 228×10^9 tons (or a weighted carbon density of 124 ton/ha). The two weighted carbon densities differ by a factor of 1.5. Other estimates of the weighted carbon density of tropical forests are 114 ton/ha (*7*) and 165 ton/ha (*8*).

The data base for estimating the biomass or carbon pool in tropical forests is poor at best (*6*). The few studies in which the biomass of tropical forests has been measured by destructive sampling cover only a small area (< 30 ha). They also tend to be concentrated in a few forest life zones [10 out of 33, as defined by Holdridge (*9*)], while other life zones, particularly the very wet and very dry, have barely been studied.

In contrast, much more information on standing timber volumes in tropical forests from a broader geographical area and from more and larger plots is available. We now present our derivation of another estimate of the total biomass or carbon pool and weighted biomass density of tropical forests based on volumes of forest stands. For this new estimate we used data from the recent reports of the Food and Agriculture Organization (FAO) (*10*). These reports give detailed information on forest areas and corresponding stand volumes within the tropical regions of America, Africa, and Asia, country by country. Seventy-six countries were surveyed, covering 97 percent of the area that lies in the tropical belt.

There are two major forest categories according to the FAO study: closed forests in which the forest stories cover a high proportion of the ground and lack a continuous dense grass cover and open forests in which the mixed broadleaf-grassland tree formation has a continuous dense grass layer and the tree canopy covers more than 10 percent of the ground. The former may be dominated by broadleaf (evergreen, deciduous, or semi-deciduous) or coniferous species growing in wet, moist, or dry climates. Within these two broad classes of forest types there are further classifications according to degree of disturbance, productiveness, or unproductiveness (see Table 2, notes).

To estimate the biomass for tropical forest vegetation, we used the volume and area data in the FAO reports (*10*). Stand volume is defined as the gross volume over bark (VOB) of the free bole (from stump to crown point or first main branch, generally to a top diameter of 7 cm) for all living trees with a diameter at breast height ≥ 10 cm. In general, the

Table 1. Ratio of total biomass to wood biomass for a variety of tropical forests.

Life zone	Biomass (ton /ha)		Ratio of total biomass to stemwood biomass	Reference
	Stemwood	Total		
Tropical premontane wet forest	416.1	689.7	1.7	(*12*)
	272.8	475.3	1.7	(*12*)
Tropical lower montane rain forest	385.0	552.8	1.4	(*13*)
Tropical montane wet forest	269.7	415.8	1.5	(*26*)
	269.7	374.0	1.4	(*27*)
Tropical wet forest	229.5	415.2	1.8	(*28*)
	201.3	348.0	1.7	(*28*)
	110.5	171.7	1.6	(*28*)
	297.0	501.3	1.7	(*12*)
Tropical moist forest	346.0	473.7	1.4	(*29, 14*)
	297.5	394.3	1.3	(*15*)
	298.9	473.1	1.6	(*15*)
	206.0	324.2	1.6	(*30*)
	230.0	361.8	1.6	(*16*)
Tropical premontane moist forest	63.5	170.3	2.7*	(*15*)
Subtropical wet forest	153.3	271.8	1.8	(*31*)
Subtropical moist forest	135.0	230.4	1.7	(*15*)
	209	290.8	1.4	(*16*)
	112	157.0	1.4	(*16*)
Subtropical dry forest	55	78.1	1.4	(*16*)
	29.0	89.8	3.1†	(*32*)
Mean (standard error)			1.6 (0.04)	

*Not included in the calculation of the mean because these two forests are typical of open forest formations. Trees in this formation tend to branch more and have a larger proportion of their biomass in branches and below ground.