Seismicity of Rockfalls and Avalanches at Three
Cascade Range Volcanoes: Implications for Seismic Detection
of Hazardous Mass Movements

by Robert D. Norris

Abstract  This study reviews seismograms from 14 rockfalls and avalanches of moderate to large volume \(10^4 \text{ to } 10^7 \text{ m}^3\) at Mount St. Helens, Mount Adams, and Mount Rainier in the Cascade Range of Washington to investigate how variations in source volume, source materials, track materials, and failure modes affect avalanche seismicity. The largest signals were generated by rockfalls at Mount St. Helens and debris avalanches at Mount Rainier that initiated as block failures. At Mount St. Helens, several rockfalls that originated as block failures near the crater rim descended slopes with similar profiles, and appear to show a linear or nearly linear relation between source volume and seismogram amplitude. Those that fell over an extended period of time were poorly recorded at the reference seismic station and did not show this correlation.

Multiple seismograms from three of the four instrumentally recorded debris avalanches at Mount Rainier indicate a tendency of unstable slopes there to fail progressively, a pattern that has important implications for the mass-movement hazard at Mount Rainier. Seismic evidence shows that the Little Tahoma rockfall avalanches in December 1963 occurred on 6 December, over a week earlier than previously reported.

Mass movements that have been seismically detected span the spectrum of rapid flowage events, from water surges and debris flows to dry rock, debris, ice, and snow avalanches. The success in identifying and in some cases locating these events in near real time demonstrates that local and regional seismic networks can play a valuable role in reducing hazards from large, rapid mass movements.

Introduction

The operation of short-period seismograph stations in the Cascade Range has yielded a considerable data base on its seismicity. Although the purpose of these stations was originally to locate earthquakes, many seismograms have also been recorded from nonearthquake sources such as glacier movements, rock, debris, and snow avalanches, debris flows, and water surges (Weaver et al., 1990). The largest instrumentally recorded mass movements in the Cascade Range have occurred at Mount St. Helens, Mount Adams, and Mount Rainier in southern Washington State. Although these three stratovolcanoes have generated at least 14 instrumentally recorded rock, debris, snow, and ice avalanches of moderate to large volume \(10^4 \text{ to } 10^7 \text{ m}^3\) since the early 1960s, only a few of the associated seismic signals have been investigated in detail. Much larger debris flows and avalanches have occurred at each of these volcanoes in the past 10,000 yr (Crandell and Waldron, 1956; Hausback and Swanson, 1990; Scott et al., 1990) and such mass movements pose a significant geologic hazard to current population centers in their vicinities, particularly near Mount Rainier (Swanson et al., 1992).

This article is an analysis of seismic signals from the largest instrumentally recorded rockfalls and avalanches at these three volcanoes. At Mount St. Helens, seismic signals from four rockfalls that occurred on slopes with similar profiles generated seismic signals that show a linear relation between signal amplitude and source volume. These are compared with seismograms from snow avalanches at Mount St. Helens and a large ice avalanche at Mount Adams. At Mount Rainier, seismograms from three debris avalanches are analyzed to interpret the failure history and average velocity of each avalanche; in each case, seismic evidence shows that slope
failure occurred intermittently over a period of minutes to hours. Digital seismic data were used to locate debris avalanches from Curtis Ridge in 1989 and 1992 within a few minutes of their occurrence (Norris, 1989; Malone et al., 1991; University of Washington earthquake catalog, 1992). This, in addition to recent advances in real-time seismic detection of debris flows at all three volcanoes (Brantley et al., 1985; Jonientz-Trisler and Qamar, 1989; Jonientz-Trisler and Driedger, 1990), at Redoubt volcano in Alaska (Brantley, 1990), and at Mount Pinatubo in the Philippines (Hadley and LaHusen, 1991), indicates that large, rapid mass movements are seismogenic regardless of source materials and nature of flow, demonstrating the potential of local and regional seismic networks for reducing the hazards from these events.

Data Selection

All 14 rockfalls and avalanches were of sufficient size to record on the seismograph station at Longmire, Washington (see Fig. 1); these recordings formed the basis for this study. Those at Mount St. Helens and Mount Adams were described in unpublished monthly reports written by the staff of the Cascades Volcano Observatory (CVO) operated by the U.S. Geological Survey in Vancouver, Washington, and additional information was obtained during discussions with CVO scientists. Three of the four debris avalanches at Mount Rainier have been described in previous reports (Crandell and Fahnestock, 1965; Fahnestock, 1978; Frank, 1985; Norris, 1989; Malone et al., 1991). The estimated source volumes range from 0.5 to 110 × 10^3 m^3, except for three snow avalanches of uncertain volume. Source and track materials varied from nearly all rock to ice and snow with only a few percent rock (Cascade Volcano Observatory, unpublished data, 1981, 1983); the modes of detachment varied from slides or falls of single blocks to falls of loose debris occurring over a period of hours or days. The 18 May rockslide-avalanche at Mount St. Helens (Voight et al., 1981; Glicken, 1990) is not included here because of the complexity of its seismogram, which received energy from earthquake and volcanic explosion sources in addition to mass movement.

The seismograms were obtained from the short-period components of the WWSSN seismograph station at Longmire, Washington (LON in Fig. 1). From August 1962 through early 1989 these components consisted of three Benioff seismometers that recorded photographically at the site at a gain of 100,000; since then, the vertical component has been recorded on a helicorder. This long-term consistency makes LON ideal for comparing seismic events widely separated in time. Although digital recordings of seismic events in the Pacific Northwest have been available since 1980, such recordings exist for only eight of the 14 avalanches and some do not include the entire signal. For these reasons, digital trace data were not used in this study.

Station LON is well located for a study of avalanche seismicity at these three volcanoes. The epicentral distances from LON to Mount St. Helens and Mount Adams are nearly equal at 67 and 64.5 km, respectively; this distance allows complete on-scale recording of large superficial seismic events at both volcanoes and facilitates comparisons between their seismic signals. In addition, the 67 km distance minimizes the effects of variations in the avalanche source area within the 2-km-wide crater of Mount St. Helens.

Figures 2 through 4 display the seismograms from eight of the 14 rockfalls and avalanches used in this study; these reproductions were made from digital scans of the original seismic records on a UMAX flatbed scanner, which were subsequently retouched on a Macintosh workstation to enhance signal clarity and contrast. Not all signals discussed here are shown; some of the snow avalanches were too small to reproduce well, and a malfunction of the LON helicorder during the October 1992 debris avalanche at Mount Rainier resulted in an incomplete recording of that event.

Most of the signals have characteristics typical of avalanches, including emergent onsets, low maximum amplitude relative to duration, and indistinct phases (Malone, 1983). Although limited, this data set allows analysis of signals from avalanches with a wide range of source volumes, failure modes, source materials, and track materials.

Avalanche Settings

Rockfalls and Avalanches at Mount St. Helens and Mount Adams

Since its formation on 18 May 1980, the crater of Mount St. Helens has been a valuable laboratory for seismic observation of mass-wasting processes (Mills, 1991). In the process of routine monitoring of activity in the crater, geoscientists from the Cascades Volcano Observatory studied six large rockfalls in 1981. Using airphotos and field measurements, they estimated the source volume and mass of each rockfall. The source volumes have an error range of ±50% (Robin Holcomb, personal comm., 1991). All rockfalls had source areas near the crater rim (Fig. 5a), in cliffs of thin-bedded andesite lava flows, breccia, and tephra.

In 1980 and 1981 the newly formed crater was an excellent location for observing how physical parameters of rockfalls affect their seismic characteristics, as the morphology of the crater walls was much more uniform than it is now. As Figure 5b shows, slope profiles did not vary much from one avalanche source area to another, and crater wall heights at the source areas varied less than 10% from the average of 557 m above the cra-
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Debris Avalanches consist of blocks of brecciated lava and scoria in a fragmented, sandy matrix. Seismograms have been identified at LON for all but the Gibraltar Rock avalanche, which had an estimated volume between 30,000 and 50,000 m³ (Frank, 1985). The reasons why the Gibraltar Rock event was undetected are uncertain, but based on the observations at Mount St. Helens, it may have fallen as small rockfalls undetectable at LON.

Rockfall and Avalanche-Seismogram Correlations: Mount St. Helens and Mount Adams

Rockfalls at Mount St. Helens, 14 January, 27 May, 27 June, and 3 October 1981

Seismograms of these four rockfalls taken from stations near Mount St. Helens (Fig. 2) consist of well-defined climax events preceded and followed by minor rockfall activity, with the climax events recording well beyond the local Mount St. Helens network. Observers

![Image of a map showing the location of seismograph stations LON, TUM, and SEA relative to Mount St. Helens, Mount Rainier, Mount Adams, and major geographical and cultural features in western Washington State.](image-url)
of the 27 May event reported that a large, tabular block of rock and debris slid from the upper west crater wall and disintegrated almost immediately, often falling free, generating a large seismic signal. A large dust plume was raised when the rockfall struck a talus apron near the base of the crater wall (CVO, unpublished data, 1981). A similar dust plume was observed on radar following the October event, and visual observations confirmed that another large block had fallen from the crater rim. The presence of other climax events for the 14 January and 27 June rockfalls indicate the fall of other large blocks of rock and debris. All four falls occurred during relatively quiet intervals between periods of dome growth, allowing the seismograms to be easily identified. Field reports indicate that they occurred when the crater snowpack was low; the avalanche tracks and deposits contained little snow.

Seismograms from the 14 January, 27 May and 27 June climax events are markedly similar, on LON-SPZ they show a teardrop or spindle-shaped envelope with maximum amplitudes occurring 25 to 30 sec. after onset, and durations are equal to within 6 sec. (see Fig. 2 and Table 1). This similarity suggested a possible relation between the dimensions of the seismograms and the source volumes calculated for these rockfalls. As their durations varied little, I plotted the maximum signal amplitude against the estimated source volumes for these three rockfalls, as shown in Figure 6a. Signal amplitude appears to show a linear increase with volume, such that

\[ V = 18889A + 80071 \]

\[ (r = 0.99), \]  

where \( V \) = estimated source volume and \( A \) = maximum signal amplitude.

The 3 October 1981 seismogram has a different envelope than the previous 1981 events, with two amplitude maxima approximately 50 sec apart in the seismogram (see Fig. 2). This 50-sec interval is constant on seismograms from more distant stations, indicating the presence of two overlapping subevents in the signal. This double nature explains both its extended duration compared to the earlier 1981 events and its apparent departure from the linear relation between amplitude and source volume shown in Figure 6a. The maximum amplitude of 19.0 mm does not take into account the seismic signal from the first subevent.

The October 1981 rockfall allows a simple test to be made of equation (1); the sum of the volumes rep-

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**Rockfall and Avalanche Seismograms (LON-SPNS Component)**

<table>
<thead>
<tr>
<th>Mt. St. Helens</th>
<th>Envelopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/27/81</td>
<td><img src="image1" alt="Envelope" /></td>
</tr>
<tr>
<td>01/14/81</td>
<td><img src="image2" alt="Envelope" /></td>
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<tr>
<td>06/27/81</td>
<td><img src="image3" alt="Envelope" /></td>
</tr>
<tr>
<td>10/03/81</td>
<td><img src="image4" alt="Envelope" /></td>
</tr>
</tbody>
</table>

**Mount Adams**

| 07/15/83      | ![Envelope](image5) |

Figure 2. Seismograms and envelope tracings from the large rockfalls at Mount St. Helens and the Mount Adams ice avalanche. Part of the January 1981 seismogram was obscured at the seam of the seismograph drum, resulting in the gap in the signals.
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represented by the two subevents should agree with the $5.9 \times 10^5$ m$^3$ volume estimate obtained from field measurements. From equation (1),

$$V_{tot} = 18889(A_1 + A_2) + 2(80071),$$  \hspace{1cm} (2)

where $A_1$ and $A_2$ are the amplitudes of the two subevents. The subevent amplitudes are 9.4 and 19.0 mm, yielding an estimated $V_{tot}$ of $7.0 \times 10^5$ m$^3$. This exceeds the field estimate by about 19%, but is well within the 50% error range of the field estimate, as shown in Figure 6a.

This analysis of seismograms from these rockfalls appears to show that signal amplitude varies linearly with the source volume, in the limited case of rockfalls originating as large block failures that descend slopes with similar profiles and track materials. However, many rockfalls both at Mount St. Helens and Mount Rainier do not fit these criteria; many consist of multiple slope failures and generate seismograms that are considerably more complex (see Figs. 2, 3, and 4). In such cases, a single-amplitude measurement may not provide an accurate measure of rockfall volume.

Figure 3. Seismograms from rockfall avalanches at Curtis Ridge. The initial event at 17:06 UTC on 08/16/89 was obscured by the main event shown above. A brief section of traces was lost in the seam of the seismograph drum.
Seismograms from Little Tahoma Rockfalls, Mount Rainier

December 6, 1963
LON-SPNS Component

Figure 4. Two seismograms from the Little Tahoma rockfall avalanche sequence at Mount Rainier. The dotted line shows the approximate envelope area of the main rockfall signal at 17:31 UTC; its unequal half-amplitudes result from passage of cycles beyond the bottom edge of the seismograph record.
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Figure 5. (a) Schematic view of the crater of Mount St. Helens showing approximate source areas and runout zones of the rockfalls discussed in the text; contours and lava dome are shown as of October 1980. Rockfall deposits are modified from unpublished sketches by scientists from the Cascade Volcano Observatory. (b) Slope profiles of five rockfalls and the January 1989 snow avalanche in the crater of Mount St. Helens. The profiles of the five rockfalls are shown from the top of the source area to the change of slope at the relatively flat 1981 crater floor.
Rockfall and Snow Avalanche Sequence, Mount St. Helens, 4 through 6 December 1981

Several prominent rockfall sequences were reported by CVO field crews during the fall months of 1981; these generated visually impressive swarms of rockfall signals on stations near the crater, but lacked a well-defined climax event. One of these sequences that occurred from 4 through 6 December 1981 is of particular interest because it removed approximately $19 \times 10^6$ m$^3$ of rock and debris from the crater rim, the largest source volume among the six rockfalls studied in 1981 (Robin Holcomb, personal comm., 1991).

In contrast to the four large block rockfalls discussed in the previous section, most of this mass fell in hundreds of small rockfalls undetectable at LON. On the 5 and 6 of December a total of 21 hr of rockfall activity was recorded on a station 1.6 km from the source area, including an intense swarm lasting 4 hr (CVO, unpublished data, 1981). Only three rockfall signals were large enough to record at LON, with amplitudes of about 2.0, 3.0, and 7.6 mm. The latter event is close to the 8.1 mm amplitude of the 27 June 1981 large block rockfall, which was only about 12% of the volume of the 4 through 6 December series. The presence of these three larger signals agrees with the morphology of the deposit, which suggests that the series included one or more large rockfalls (CVO, unpublished data, 1981).

The low seismicity of this sequence relative to block failures of much smaller volume is a natural consequence of the linear relation between signal amplitude and volume. From equation (1), the total volume of rock moved in a series of $n$ dynamically independent rockfalls can be expressed as

$$V_{\text{tot}} = V_1 + V_2 + V_3 \cdots V_n = \sum_i^n R a_i + C, \quad (3)$$

and the amplitude $a_i$ of any signal in the series is

$$a_i = \frac{V_i - C}{R}, \quad (4)$$

so as $V_i$ decreases toward the empirical constant of $C$ (80071 m$^3$ at LON), the amplitude approaches zero at LON and so is undetectable there. For a rockfall of a given volume, it becomes difficult to observe the relation between its volume and the signal amplitude if it

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### Table 1

Summary of Data: Rockfalls and Avalanches

<table>
<thead>
<tr>
<th>Date (m/d/yr)</th>
<th>Volume, $10^3$ m$^3$</th>
<th>LON Amplitude, mm</th>
<th>Vertical Drop, m</th>
<th>Avg. Slope (°)</th>
<th>Source Materials</th>
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<tbody>
<tr>
<td><strong>Large-Block Rockfalls at Mount St. Helens</strong></td>
<td></td>
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<tr>
<td>05/27/81</td>
<td>1.3*</td>
<td>2.8</td>
<td>560 m$^3$</td>
<td>46.6°</td>
<td>rock/debris</td>
</tr>
<tr>
<td>01/14/81</td>
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<td>5.5</td>
<td>500 m$^3$</td>
<td>41.2°</td>
<td>rock/debris</td>
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<td>06/27/81</td>
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<td>8.1</td>
<td>600 m$^3$</td>
<td>52.0°</td>
<td>rock/debris</td>
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<tr>
<td>10/03/81</td>
<td>5.9*</td>
<td>9.4, 19.0</td>
<td>545 m$^3$</td>
<td>49.1°</td>
<td>rock/debris</td>
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<td><strong>Other Rockfalls and Avalanches at Mount St. Helens</strong></td>
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<td>12/05/81</td>
<td>19*</td>
<td>2.0, 3.0, 7.6</td>
<td>560 m$^3$</td>
<td>47.7°</td>
<td>rock/snow</td>
</tr>
<tr>
<td>05/30/83</td>
<td>—</td>
<td>3.1</td>
<td>—</td>
<td>—</td>
<td>snow</td>
</tr>
<tr>
<td>05/23/84</td>
<td>—</td>
<td>12.5</td>
<td>—</td>
<td>—</td>
<td>snow</td>
</tr>
<tr>
<td>03/12/88</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>snow</td>
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<tr>
<td>01/13/89</td>
<td>5.2*</td>
<td>2.3</td>
<td>560 m$^3$</td>
<td>47.7°</td>
<td>snow/rock (−3% rock)</td>
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<td><strong>Ice/Snow Avalanche at Mount Adams</strong></td>
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<tr>
<td>07/15/83</td>
<td>10–24</td>
<td>4.5</td>
<td>1341 m (avg.)</td>
<td>20.0°</td>
<td>ice/snow (−3% rock)</td>
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<td><strong>Debris Avalanches at Mount Rainier</strong></td>
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<tr>
<td>12/06/63</td>
<td>110</td>
<td>&gt;200</td>
<td>1890 m</td>
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<td>rock/debris</td>
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<td>06/21/74</td>
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<td>67</td>
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<td>08/16/89</td>
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<td>78</td>
<td>1580 m</td>
<td>21.5°</td>
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<td>10/23/92</td>
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<td>—</td>
<td>1032 m</td>
<td>29.1°</td>
<td>rock/debris</td>
</tr>
</tbody>
</table>

*Estimated source volumes (Robin Holcomb, personal comm., 1991).

*Measured from crater rim to change of slope at 10/81 crater floor.

*Estimated bulk volume of deposit (Mills, 1991).

*Measured from top of source area to maximum runout.

*CVO, unpublished data, 1983.
occurs in more than a few discrete falls; in addition, these may be confused with other rockfalls occurring in adjacent areas. Successful correlations between volume and signal amplitude may be limited to rockfalls occurring as simple block failures.

Snow and Ice Avalanches at Mount St. Helens and Mount Adams

Snow avalanches are common in the crater of Mount St. Helens during the winter and spring months, but few have been studied in detail because of the difficulty in gaining access to the crater in those seasons. Large "dirty snow" avalanches, so named because they consisted partly of rock debris, were correlated with seismograms on 30 May 1983, 23 May 1984, 12 March 1988, and 13 January 1989. The January 1989 avalanche is one of the largest to occur in the crater since 1980 and the only one to be examined in detail in the field. When it was investigated in July 1989, the bulk volume was estimated to be about $5.2 \times 10^5$ m$^3$, including about $1 \times 10^5$ m$^3$ of rock debris (Mills, 1991). The original bulk volume of snow is unknown, but the rock volume is comparable to the bulk volumes of rock deposited by the four large-block rockfalls described previously. The seismogram amplitude is only 2.3 mm. For comparison, equation (1) shows that a signal of this size would be generated by a large-block rockfall of about $1.2 \times 10^5$ m$^3$ on the dry, snow-free track that was typical of those rockfalls.

The ice and snow avalanche that occurred at Mount Adams on 15 July 1983 is only the second ice avalanche in the Cascade Range to be seismically recorded; the first was a collapse of a portion of the Sherman Glacier into the Sherman Crater of Mount Baker in 1977 (Weaver and Malone, 1979). It began as a large block slide near the 3470-m level in ice of the White Salmon Glacier, and removed a complete section of the glacier down to bedrock. The block rapidly disintegrated into an ice avalanche, which descended the Avalanche Glacier for 4 km and ended in two major distributary lobes with distal margins near the 2070 and 2200-m levels. The deposit consisted of glacier ice, snow, and approximately 3% rock debris (CVO, unpublished report, 1983).

Photographs taken during an overflight on 15 July and from the ground on 16 July enabled me to establish the locations of the scarps at the headwall and sides of the missing block within a few tens of meters on 1:24,000-scale topographic maps; however, the lower margin is difficult to discern. I estimated a thickness by comparing the height of the headwall scarp with known heights of nearby cliffs; the most prominent scarp appears to be between 30- and 40-m high, which is a reasonable ice depth for a Cascade glacier on a steep slope (Carolyn Driedger, personal comm., 1991). The maximum width is approximately 180 m. I approximated the missing section of glacier ice as a slab with a uniform thickness between 30 and 40 m, broadly U-shaped in cross section to match the concavity of the slope. Using these assumptions, the block appears to be between 10 and $24 \times 10^5$ m$^3$ in volume.

The avalanche generated an emergent (gradually increasing) seismic signal at 05:31 UTC on 15 July on stations near Mount St. Helens and Mount Rainier; the LON seismogram is shown in Figure 2. The epicentral distances to LON from this avalanche and the January 1989 avalanche at Mount St. Helens are nearly equal at 64.5 and 67 km, respectively; the respective signal amplitudes were 4.5 and 2.3 mm. Although their source volumes are not well constrained and they occurred on

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**Figure 6.** (a) Least-squares linear regression of signal amplitude on LON-Z versus estimated source volume from three of the four large-block rockfalls in the crater of Mount St. Helens. (b) Least-squares linear regression of signal amplitude versus envelope area for ten rock and snow avalanches at Mount St. Helens and three Makaopuhi Crater rockfalls.
different slopes, these two avalanches demonstrate that mass movements of snow and glacier ice with volumes on the order of $10^5$ to $10^6$ m$^3$ can be detected by currently operating short-period seismograph stations to distances on the order of 60 km.

Avalanche-Seismogram Correlations: Mount Rainier

As LON is much closer to the source areas of the debris avalanches at Mount Rainier, much more detail is visible in the seismograms compared to those at Mount St. Helens and Mount Adams. However, correlations between seismogram amplitude and avalanche volume have not been successful at Mount Rainier because of poorly constrained volumes, differences in runout lengths between avalanches, saturation of the LON short-period records by the Little Tahoma rockfall, and mechanical failure of the LON helicopter during the 1992 debris avalanche at Curtis Ridge.


The east face of Curtis Ridge is an active source area for rockfalls of $10^4$ to $10^5$ m$^3$ in volume (Frank, 1985). The three largest known since 1974 flowed 2 to 4 km down the Winthrop Glacier as debris avalanches, and two of these three were seismically recorded at LON (see Fig. 3). Photographs were taken of the source areas and deposits shortly after the 1989 and 1992 avalanches, allowing me to accurately map the source areas and deposits on 1:24,000-scale topographic maps. The only photograph available from 1974 shows the deposit at a very oblique angle, so its extent is less certain.

The 21 June 1974 debris avalanche fell from the 3500-m level of Curtis Ridge and traveled 2 km down the Winthrop Glacier (Frank, 1985); its date and time of occurrence were not known prior to this study, when its seismogram was discovered on LON. As shown in Figure 3, the main event at 08:53 UTC consists of two pulses with a total duration of 275 sec, followed by smaller failures at 12:25 and 12:55 UTC. The bulk volume of the deposit is estimated to be within 0.5- to 1.0 x $10^5$ m$^3$ (Frank, 1985).

Beginning at 17:06 UTC on 16 August 1989, another large debris avalanche fell from the 3400-m level on Curtis Ridge, about 200 m southeast of the source area for the 1974 avalanche. It descended the Winthrop Glacier for 4 km, leaving a multilobed deposit of rock and debris with a bulk volume of 1.0 to 5.0 x $10^5$ m$^3$. The lowest lobe reached an elevation near 1950 m. The failure removed the projecting corner of a cliff face about 120-m high and some overlying bedded lava and tephra units with a total surface area of about 15,000 m$^2$. The newly exposed cliff face included a central concave section, indicating that failure may have occurred partly by slumping. The thickness of the missing material is difficult to estimate but appears to have been much thinner than its height and width; if between 10- and 30-m thick, the source volume would be between 150,000 and 450,000 m$^3$. If 40% void space is generated during its descent, the corresponding deposit volume would be 250,000 to 750,000 m$^3$, about 150% of the volume range obtained from mapping of the deposit itself.

The LON station recorded three precursory failures at 17:06, 17:14, and 17:15, followed by the main failure of 17:21. The 17:21 event was visible for 9 min on the seismogram from the station at Camp Schurman (RCS in Fig. 7) and was recorded to distances of 200 km across the regional seismic network in Washington and northern Oregon (Norris, 1989; Malone et al., 1991). Three of the signals are displayed in Figure 3; the initial event at 1706 is partly obscured by the main event at 1721.

The event at 17:14 was located with standard University of Washington earthquake location techniques, using digital trace data from 14 stations. Five stations were within 20 km of the source, which was constrained to be within 1 km of a seismic station at Camp Schurman on Steamboat Prow. The actual source area as determined from photographs lies 1.7 km west-southwest of this station, as shown in Figure 7. Officials at Mount Rainier National Park were advised of the event by University of Washington and U.S. Geological Survey personnel, and Park rangers immediately began accounting for all climbing parties to ensure none were missing. Poor weather prevented visual confirmation of the avalanche until the following day, making this the first significant debris avalanche at Mount Rainier to be identified and located from seismic data alone.

At 15:58 UTC on 23 October 1992, the eastern section of the cliff face created by the August 1989 debris avalanche failed, again taking some overlying bedded lava and tephra units with it. The avalanche was observed by motorist parked at the Mather Overlook on U.S. Highway 410 east of Mount Rainier, and was located by the University of Washington using digital trace data from seven stations. Unfortunately, the LON helicopter failed during the seismic signal and made an incomplete recording. The failure area is difficult to discern from that of the 1989 avalanche, but the deposit on the Winthrop Glacier was very close in area to the 1974 deposit. As the deposits of all three avalanches appear to be quite thin (<1 m), this implies that its bulk volume is similar to the 1974 avalanche, about 0.5 to 1.0 x $10^5$ m$^3$.

Little Tahoma Debris Avalanche, December 1963

The largest debris avalanche that has occurred in the period of modern instrumental seismic monitoring of the Cascade Range (since 1960) fell from the Little Tahoma peak on the east slope of Mount Rainier in December 1963. A series of failures from a buttress on the north
face of Little Tahoma left at least seven separate avalanche deposits in the White River valley below the terminus of the Emmons Glacier, with a total volume estimated at 11 million m³. The deposits were examined in detail and mapped by Crandell and Fahnestock (1965), who studied them during the following summer. The largest lobe moved approximately 1890 m vertically and 8370 m horizontally, stopping 600 m beyond the terminal moraine constructed by the Emmons Glacier during its Neoglacial maximum advance.

The time of the avalanche was originally placed around noon on 14 December, based on a report of a "loud, sharp boom" heard by two U.S. Forest Service rangers at that time, and the sighting of the avalanche deposit when clouds lifted that afternoon (Crandell and Fahnestock, 1965; Fahnestock, 1978). The short-period records of the Longmire station were searched for a seismogram from the avalanche, but no significant seismic events were found on the 14th. It was uncertain at that time whether the rockfalls had been seismically recorded.

After studying the 1989 Curtis Ridge event, however, it seemed likely that such a large avalanche would have generated a seismogram; the volume of the Little Tahoma sequence was more than an order of magnitude larger. Accordingly, the LON and Tumwater (TUM) WWSSN station records for that period were reviewed and two large events were discovered at 14:10 and 17:31 UTC on 6 December 1963. Although there are no visual observations to link these events with the Little Tahoma debris avalanches, I believe these seismograms were generated by at least two of the seven avalanches of the series for the following reasons:

1. The events show characteristics of near-source seismograms from large rockfalls at Mt. St. Helens: emergent onsets, poorly defined phases, and fluctuating, irregular amplitudes (Malone, 1983).
2. The amplitude and duration of each event attenuate rapidly with distance, a characteristic of rockfall and avalanche signals (Tilling et al., 1975). The maximum amplitude for the 14:10 event is 78 mm on the LON-SPZ component, 1.8 mm on the short-period vertical component of the Tumwater station (TUM), 95 km from Little Tahoma, and too small to measure on the Seattle station (SEA), 101 km from Little Tahoma. The amplitude for the 17:31 event on LON-SPZ is difficult to read but exceeds 200 mm, and it

![Figure 7](attachment:Figure_7.png)

Figure 7. Schematic view of Mount Rainier showing the source areas and deposits of five debris avalanches discussed in the text relative to major features of Mount Rainier. The solid black circles denote source areas; filled octagons represent locations of source areas for the August 1989 and October 1992 debris avalanches obtained from seismic data. The October 1992 deposit covered nearly the same area as the June 1974 deposit, so little of the latter is visible.
exceeds 250 mm on the SPNS and SPEW components. It attenuates to 7.4 mm at TUM, and 2.5 mm at SEA. Attenuation of coda also occurs; signal duration for the 17:31 event drops from approximately 300 sec on LON-SPZ to 210 on TUM-SPZ, and 180 at SEA. Although TUM and SEA were operating at lower gain than LON, this accounts for only part of the large decreases in these values. For comparison, a magnitude 3.9 earthquake that occurred beneath the south flank of Mount Rainier in October 1969 had an average duration of 365 sec at TUM and 380 sec at SEA (LON was not operating during this earthquake). The attenuation pattern indicates the source area is much closer to LON than TUM and SEA, consistent with a location at Mount Rainier. Although phases were read and recorded from both avalanche signals in the LON and TUM station records, the nature of the signals was apparently not recognized at that time.

If the Little Tahoma debris avalanches actually occurred on the morning of 6 December 1963, why were the deposits not observed until 8 days later? A possible answer can be found in weather data for that week; on 6 December, 37 mm of precipitation was recorded at the weather station at Longmire, including 152 mm of snow (NOAA, Western Region Climate data). The avalanche deposit was probably obscured by clouds and fresh snow for several days; precipitation was recorded daily from 5 December through 9 December both at Longmire and Stampede Pass, 55 km northeast of the summit of Mount Rainier (Seattle Daily Times, December 1963).

Although fresh rock debris was occasionally observed on the Emmons Glacier after December 1963, the lack of identifiable avalanche signals on the LON records through the end of March 1964 suggests that most of the deposit was emplaced on 6 December. However, there were 15 days between 6 December 1963 and 31 March 1964 when the LON short-period components were not operating or are missing from archives, leaving open the possibility that later avalanche signals may have been missed.

Hazard Implications

Seismic Identification and Location of Rockfalls and Avalanches

The experience with the large rockfalls at Mount St. Helens and debris avalanches at Mount Rainier shows that such events can be quickly identified and located from seismic data, provided there are enough nearby stations to allow the events to be located in spite of poor-quality, emergent arrivals. At Mount Rainier, the 1989 and 1992 Curtis Ridge debris avalanches were located using digital seismic data from the regional seismic network in Washington and northern Oregon, including five stations within 20 km of the source. This local network of five stations has also been used to identify debris flows originating in glacier outbursts from the South Tahoma glacier and others (Joniertz-Trisler and Driedger, 1990). Other volcanoes in the Cascade Range with local seismic networks of comparable or greater station density include Mount St. Helens and Lassen Peak; at Mount St. Helens, rockfalls have been seismically identified and located since 1980 (University of Washington earthquake catalog, 1980). Rockfalls or avalanches occurring in areas of low station density may be recognized only in retrospect, as was the case with the Mount Adams ice avalanche. The track materials underlying a moving avalanche do not seem to greatly affect the process of seismogram generation. The four debris avalanches at Mount Rainier, which descended glaciers for much of their length, were generally as well recorded by the regional seismograph network in Washington State as the large-block rockfalls at Mount St. Helens, which had track materials of rock and debris.

Until recently, real-time identification of rockfalls and other mass movements depended entirely on visual monitoring of seismic signals from stations within a few kilometers of the source areas by experienced personnel who could quickly discern between these signals and similar-appearing ones such as large local earthquakes. This has been particularly true of active volcanoes, where seismograms from debris avalanches can be difficult to discern from those generated by gas emissions or small eruptions. However, automated seismic debris flow detection systems successfully detected eruption-induced debris flows from Redoubt Volcano in 1990 (Brantley, 1990) and rainfall-induced flows from Mount Pinatubo following its 1991 eruptions (Hadley and LaHusen, 1991). Computer-based systems of these kinds will play an increasingly important part in providing real-time warnings of large mass movements in the future.

Seismic Constraints on Average Velocity of the Little Tahoma Debris Avalanche, Mount Rainier

The Little Tahoma debris avalanche provides an opportunity to test if seismic signals can be used to calculate an approximate average velocity of an avalanche by means of a simple division of runout length by signal duration. This average can be compared with velocities obtained from measurements of avalanche runup height on valley walls made by Crandell and Fahnestock (1965). Using photographs and maps of the Little Tahoma rockfalls from their report, I mapped the approximate centerline of the longest deposit (unit number 3 of Crandell and Fahnestock) on 1:24,000-scale topographic maps to obtain an approximate runout length. The length obtained was 8370 m; dividing this distance by the signal durations on LON-SPZ yields an average velocity of 26.4 m/sec for both the 14:10 and 17:31 avalanche events, somewhat slower than the instantaneous velocities of 29.1 to 42.5 m/sec calculated from runup features.
The 26.4-m/sec average velocity is a minimum value, as the avalanche path was probably much more sinuous than indicated by its average centerline; for example, Crandell and Fahnestock (1965) report that avalanche unit number 3 was moving nearly perpendicular to the trend of the valley near the Neoglacial terminal moraine of the Emmons Glacier. In addition, the multiple amplitude maxima present in the signals probably indicate that more than one avalanche unit was in motion at the same time, so travel time of individual units may have been shorter than the duration of the signal. Both of these circumstances indicate that the average velocity was probably higher. The velocities estimated from the largest seismic signals in the three Curtis Ridge debris avalanches in 1974, 1989, and 1992 are even slower, at 9.8, 14.3, and 12.2 m/sec, respectively. The low average velocities derived for all four debris avalanches at Mount Rainier suggest that caution should be used when interpreting avalanche velocity from seismic signals, particularly in light of the rapid attenuation of rockfall signals with distance.

Progressive Failure of Rock Faces at Mount Rainier

The presence of multiple signals separated by minutes or hours in three of the four debris avalanches suggests that failure of steep rock faces at Mount Rainier often occurs progressively, an interpretation backed by Crandell and Fahnestock's (1965) identification of seven separate units in the December 1963 avalanche deposit. Although only two avalanche signals have been identified on 6 December, the multiple amplitude maxima in both signals suggest that more than one unit was in motion during each signal (see Fig. 4). The striking contrast between the similarity of their duration and their large differences in amplitude agrees with the pattern shown by the Mount St. Helens rockfalls, in which signal amplitude appears to be much more sensitive to changes in volume than duration.

This tendency for progressive failure should be noted in any assessment of hazards from large debris avalanches at Mount Rainier; people should stay well clear of the runout zone of any major avalanche in the future, particularly during the following few days. The danger of subsequent avalanches is high, and as shown by the Little Tahoma sequence, the first such event is not always the largest.

Discussion

The observation of a consistent increase in seismogram amplitude with the estimated source volume of block rockfalls at Mount St. Helens contrasts with the findings of earlier studies of rockfall seismicity. Tilling et al. (1975) observed seismic signals of rockfalls in Makaopuhi Crater on the east rift zone of Kilauea Volcano, Hawaii, in 1972 and found a poor correlation between the volume of observed rockfalls and the duration of their seismic signals. In a recent study of mass-wasting by rockfall in the crater of Mount St. Helens, Mills (1991) successfully tracked overall rockfall activity levels in the crater of Mount St. Helens, using the Real-Time Seismic Amplitude Measurement system (RSAM, Murray and Endo, 1989) and reported a similar poor correlation; rockfalls that differed in volume by several orders of magnitude could be distinguished by their seismic amplitude or duration, but those closer in volume could not.

This study of rockfall seismicity differs from these previous ones in its use of seismograms from much larger rockfalls (>10^4 m^3). At West Makaopuhi, the largest individual rockfall was only around 8000 m^3 and the total volume of all the Makaopuhi rockfalls was 2.7 × 10^4 m^3, near the average size of the large block rockfalls at Mt. St. Helens chosen for this study. Mills (1991) focused on the nearly continuous minor rockfalls common in the crater of Mount St. Helens. The largest observed rockfalls in both locations saturated most of the seismic signals, preventing observation of possible relations between volume and seismogram size.

Some of the larger rockfalls at Makaopuhi Crater are similar in character to the large-block rockfalls at Mount St. Helens; they originated as discrete blocks near the crater rim, and descended similar steep slopes approximately 150-m long. Three seismograms displayed in Figure 12 of Tilling et al. (1975) show a linear relation between amplitude and envelope area that characterizes the Mount St. Helens group, as shown in Figure 6b of this article. Unfortunately, the high rockfall rate at Makaopuhi prevented detailed observations of individual rockfalls, so their signal amplitudes cannot be correlated with volume.

This study corroborates the observation made in these two previous reports that signal duration alone is a poor indicator of rockfall volume; at Mount St. Helens, signal amplitude appears to be much more sensitive to changes in volume than duration (see Fig. 6a and Table I). However, the maximum signal amplitude of the large block rockfalls at Mount St. Helens appears to show a good correlation with source volume; even taking the error ranges of the volume estimates into account, volume differences of 50% are easily discernable in the seismograms (see Fig. 2 and Table I). As a consequence of this linear relation, swarms of small dynamically independent rockfalls can transport volumes of rock equivalent to a much larger block failure without generating a large seismic signal. Seismic monitoring appears to be most useful in detecting mass movements generated by rapid block falls or slides.

It should be noted that the volume range of rockfalls and avalanches used to determine the linear relation shown in Figure 6a (10^4 to 10^5 m^3) represents only a small portion of the known volume range of mass movements on
volcanoes. Deposits of the Osceola Mudflow at Mount Rainier and the large debris avalanche at Mount Shasta between 0.30 and 0.36 Ma, two of the largest known in the Cascade Range, exceed $10^{10}$ m$^3$ (Brantley and Glicken, 1986; Scott et al., 1990). It is entirely possible that the relation between source volume and seismogram envelope may be nonlinear over larger volume ranges.

Conclusions

This study presents evidence that the seismicity of rockfalls and avalanches is governed by the time history of failure, the source materials, and the track materials involved. Those that have been seismically identified with the greatest success originated as large, rapid block failures of rock and debris. Although the data are limited, evidence from Mount St. Helens suggests that rockfalls that have the same source areas and descent paths show a linear or nearly linear relation between source volume and signal amplitude, indicating that rockfalls occurring in these circumstances may be volume-predictable from seismic records. Rockfall sequences, such as those studied earlier at Mount St. Helens and Makaopuhi Crater in Hawaii, appear to show a poor correlation between signal amplitude and volume.

The two large seismic signals that appeared on the Longmire station on 6 December 1963 have the characteristic of avalanche seismograms and may have been generated by two or more debris avalanches of the Little Tahoma sequence at Mount Rainier. If so, some or all of the avalanches may have preceded the 14 December date postulated by Crandell and Fahnestock in their 1965 report. The multiple nature of these signals and those from other debris avalanches at Mount Rainier indicate a tendency of unstable slopes there to fail progressively, a pattern that has important implications for mass-movement hazards at Mount Rainier.

Evidence from this study and others indicates that high-velocity mass movements of large volume are seismogenic regardless of composition and nature of flow; events that have been seismically detected span the spectrum of flowage events from debris flows and water surges to dry rock, ice, and snow avalanches. The experiences with large rockfalls at Mount St. Helens after 1980 and at Mount Rainier in 1989 and 1992 demonstrate that such events can be located with computer earthquake location routines currently in use (Norris, 1989; Malone et al., 1991). Local seismic networks can be an important tool for detecting large mass movements, and thus reducing the hazards associated with them.

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