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Results of Seismological Monitoring in the Cascade Range, 1962-1989: Earthquakes, eruptions, avalanches and other curiosities

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Résumé de l'article

Modern monitoring of seismic activity atCascade Range volcanoes began at Longmire on Mount Rainier in 1958. Since then, there has been an expansion of the regional seismic networks in Washington, northern Oregon and northern California. Now, the Cascade Range from Lassen Peak to Mount Shasta in the south and Newberry Volcano to Mount Baker in the north is being monitored for earthquakes as small as magnitude 2.0, and many of the strato volcanoes are monitored for non-earthquake seismic activity. This monitoring has yielded three major observations. First, tectonic earthquakes are concentrated in two segments of the Cascade Range between Mount Rainier and Mount Hood and between Mount Shasta and Lassen Peak, where as little seismicity occurs between Mount Hood and MountShasta. Second, the volcanic activity and associated phenomena at Mount St. Helens have produced intense and widely varied seismicity. And third, at the northern strato-volcanoes, signals generated by surficral events such as debris flows, icequakes, steam emissions, rockfalls and icefalls are seismically recorded. Such records have been used to alert authorities of dangerous events in progress.

Results of Seismological Monitoring in the Cascade Range, 1962-1989: Earthquakes, eruptions, avalanches and other curiosities

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Summary
Modern monitoring of seismic activity at Cascade Range volcanoes began at Longmire on Mount Rainier in 1958. Since then, there has been an expansion of the regional seismic networks in Washington, northern Oregon and northern California. Now, the Cascade Range from Lassen Peak to Mount Shasta in the south and Newberry Volcano to Mount Baker in the north is being monitored for earthquakes as small as magnitude 2.0, and many of the stratovolcanoes are monitored for non-earthquake seismic activity. This monitoring has yielded three major observations. First, tectonic earthquakes are concentrated in two segments of the Cascade Range between Mount Rainier and Mount Hood and between Mount Shasta and Lassen Peak, whereas little seismicity occurs between Mount Hood and Mount Shasta. Second, the volcanic activity and associated phenomena at Mount St. Helens have produced intense and widely varied seismicity. And third, at the northern stratovolcanoes, signals generated by surficial events such as debris flows, icequakes, steam emissions, rockfalls and icefalls are seismically recorded. Such records have been used to alert authorities of dangerous events in progress.

Introduction
When the seismicity that preceded the May 18, 1980, eruption of Mount St. Helens began on March 20, 1980, with a magnitude 4.1 earthquake, a sparse network of seismic stations in Washington state was available to locate and analyze the event. Because of the shallow nature of the calculated source depth (surface to a few kilometres at most) and the character of the earthquake coda (dominated by long-period waves greater than 0.5 seconds), the earthquake was interpreted as possibly related to a volcanic source. Appropriate managers of the United States Geological Survey (USGS) were alerted to the occurrence of this event and, within two hours, plans were made to deploy portable seismographic equipment. Subsequently, this event turned out to be a warning of catastrophic volcanic activity at Mount St. Helens.

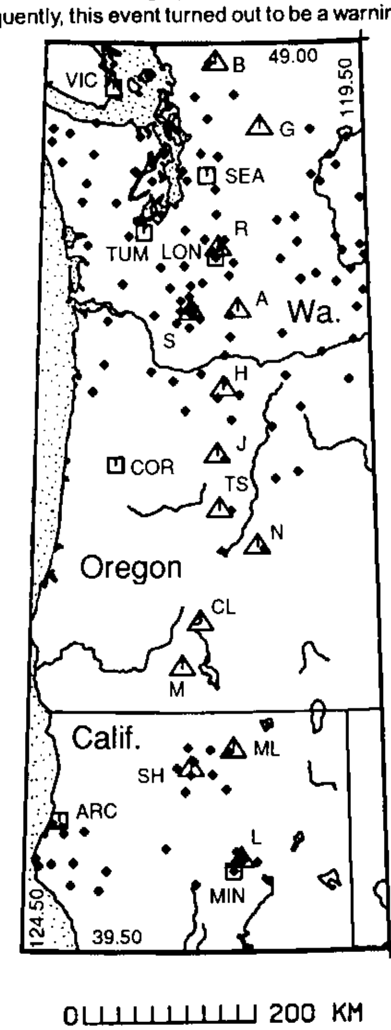

Figure 1 *Seismic stations operating near the Cascade Range. Small symbols are stations currently operating; bold squares with names are historical stations discussed in text.* ***LON*** *is part of the University of Washington network. Large triangles are stratovolcanoes, abbreviated as follows:* ***B****, Mount Baker;* ***G****, Glacier Peak;* ***R****, Mount Rainier;* ***S****, Mount St. Helens;* ***A****, Mount Adams;* ***H****, Mount Hood;* ***J****, Mount Jefferson;* ***TS****, Three Sisters;* ***N****, Newberry Volcano;* ***CL****, Crater Lake;* ***M****, Mount McLoughlin;* ***SH****, Mount Shasta;* ***ML****, Medicine Lake Volcano;* ***L****, Lassen Peak.*

The March 20, 1980, earthquake exemplified seismologists' ability to detect and analyze events that may precede or accompany hazardous volcanic activity and to issue timely warnings. This ability has steadily improved since 1958, when the first high-gain, short-period seismographic station (LON in Figure 1) on a Cascade volcano was installed on the south flank of Mount Rainier. Prior to LON, limited seismic monitoring began in 1927 when a low-gain, long-period station was installed at Mineral (MIN in Figure 1) about 15 km south-southwest of Lassen Peak; this station has operated continuously since 1939. Based on the sensitivity of regional seismographic stations installed in 1960 in southwestern Canada and the northwestern United States, combined with felt reports, Ludwin *et al.* (in press) concluded that the catalogue of earthquakes above magnitude 4.0 in Washington and Oregon is complete since 1960. The Cascade Range in California is also considered to have a complete seismic record at the magnitude 4.0 level since at least 1960 (Uhrhammer, in press). Thus, 1960 is the starting point for the modern catalogue of earthquakes in the Cascade Range of Washington, Oregon and northern California.

Since 1960, four major improvements in instrumental coverage have allowed locations to be calculated for earthquakes of small to moderate magnitudes (2.5 to 4.5) and smaller earthquakes in the Cascade Range and vicinity. First, the advent of greatly improved absolute timing coincided with the installation of the World-Wide Seismographic Station Network (including LON and COR in Figure 1) and the installation of Wood-Anderson seismometers in the Pacific Northwest. With these improvements, it became possible, beginning in 1963, to compile a complete catalogue of earthquakes magnitude 4.0 and larger using only instrumental data. Second, in 1970, a multi-station telemetered seismograph network was installed in northwestern and eastern Washington. Throughout the 1970s, this network was expanded and modified, resulting in increased sensitivity to earthquakes less than magnitude 4.0 in the northern and central portion of the Washington Cascades. Included in this expansion were permanent monitoring stations on Mount Baker and Mount St. Helens and a second station on Mount Rainier. Third, at the southern end of the range, the USGS in Menlo Park installed a network of 5 stations around Lassen Peak in 1976 and expanded the central California network to include stations that allowed monitoring of Mount Shasta and Medicine Lake in 1978-1980. Fourth, large areas of the southern Washington and northern Oregon Cascades were instrumented in 1980; some of the stations near Mount Hood replaced a local network of 16 stations that was operated around Mount Hood in 1977-1978. Routine monitoring of most of the Oregon Cascade Range south of Mount Hood also began in 1980, but was discontinued for fiscal reasons in 1982. During 1987, stations were re-installed east of the Cascade crest as far south as Newberry Volcano. The current distribution of seismic stations, as well as stations in operation prior to 1970 that were relevant to seismic monitoring of the Cascades, are shown in Figure 1. Weaver *et al.* (1982) provide additional details of the seismic monitoring history in the Cascade Range.

The seismic data from the University of Washington and the USGS-Menlo Park regional seismic networks are used to compile a catalogue of located earthquakes. At Mount Baker, Mount Rainier, Mount St. Helens, Mount Adams, Mount Hood, Newberry Volcano, Mount Shasta, Medicine Lake Volcano and Lassen Peak, continuous helicorder records are written from one or more seismic stations. From these records, seismic activity in the Cascade Range and beneath individual volcanoes is subdivided into three classes: (1) tectonic earthquakes; (2) volcanic earthquakes and volcanic-related activity (steam and ash emissions, dome avalanches and volcanic tremor) at Mount St. Helens; and (3) surficial events generated by down-slope movements of rock, snow, ice, mud, or some combination of these, that are found largely on the northern stratovolcanoes. Since 1980, virtually all tectonic earthquakes greater than about magnitude 3.0 are thought to have been located and are listed in the hypocentral catalogues; many of the Mount St. Helens volcanic earthquakes are also catalogued. Lists of the occurrence of all three event types are being developed for volcanoes where helicorder records are maintained.

In the remainder of this paper, we summarize the results of three decades of seismic monitoring in the Cascade Range. The eruption of Mount St. Helens dominates the seismological data of the Cascades since 1960, but because this eruption has been well documented (Lipman and Mullineaux, 1981; Swanson *et al.*, 1985) and an updated summary of seismic activity is available (Malone, 1990), we give only a brief overview. Tectonic earthquakes are largely confined to the segments of the range between Mount Rainier and Mount Hood and between Mount Shasta and Lassen Peak. Finally, in the last few years, there have been advances in identifying the third class of signals. Glacial outburst floods at Mount Rainier and mudflows at Mount St. Helens are now routinely identified, sometimes as the event is occurring. These advances in interpreting seismic events from surficial sources presage the ability to issue near real-time warnings of avalanches, mudflows and outburst floods.

Tectonic Earthquakes

For a range-wide perspective of instrumental seismicity, we selected well-located, greater than magnitude 2.0 earthquakes that have occurred since 1980 that met the following statistical criteria: calculated hypocentral errors of less than ±3 km, at least 6 stations used in the solutions, and root mean square (RMS) of the traveltime residuals less than 0.35 seconds. Most hypocentres have statistics considerably better than these criteria. For Washington and Oregon, our hypocentral data are taken from Ludwin *et al.* (in press) and, for California, the data are from catalogues maintained by the USGS. In plotting our catalogue (Figure 2), we excluded events greater than 30 km depth; with few exceptions, these deeper events are within the subducting Juan de Fuca or Gorda plates.

It is clear that the earthquake distribution is not uniform throughout the Cascades, and we use the sharp changes in seismicity to divide the range into four segments. The first segment, the North Cascades, is seismically quiet (Figure 2). Nearly all of the well-located crustal earthquakes in northwestern Washington are confined to the region between the eastern Olympic Mountains and the western edge of the North Cascades (Figure 2); there are few events near the Quaternary stratovolcanoes. The second segment is from Mount Rainier to Mount Hood and is the most seismically active segment. In southern Washington, the St. Helens zone (SHZ) is prominent. Although there is an hiatus of activity east of the SHZ, in general, seismicity continues in a broad zone from the area immediately west of the SHZ into southeastern Washington (Figure 2). The third segment of the range from Mount Hood to the California border is seismically very quiet (Figure 2). This segment has not been monitored continuously, but very few earthquakes were observed during the two years (1980-1982) of continuous operation of a 32-station network or since stations were re-installed in the central Oregon Cascade Range in 1987. There is a marked increase in earthquake activity in the fourth segment between Mount Shasta and Lassen Peak and also to the west along the northern California coast (Figure 2).

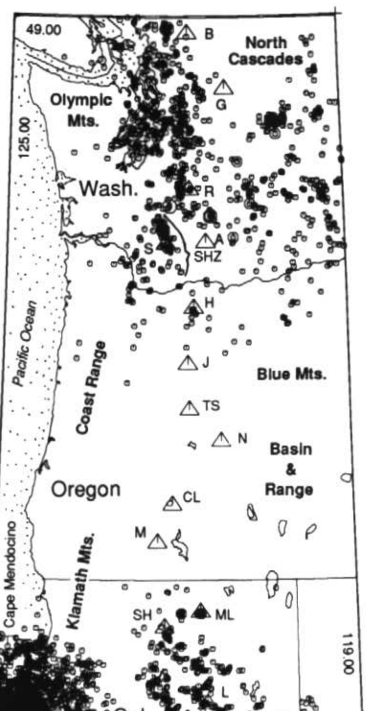

Figure 2 *Crustal earthquakes less than 30 km deep and greater than magnitude 2.0 for 1980 to 1989. Earthquake magnitudes are scaled in three sizes: smallest symbols are between magnitude 2.0 and 3.9, medium symbols are between magnitude 4.0 and 4.9, and largest symbols are magnitude 5.0 and greater. Triangles are major stratovolcanoes, abbreviated as in Figure 1.*

Seismicity of the Mount Rainier-Mount Hood segment. The most seismically active segment of the Cascade Range is that between Mount Rainier and Mount Hood (Figure 2). Since 1960, four crustal earthquakes greater than magnitude 5 have occurred in this area (Figure 3a). The most prominent feature in the seismicity distribution is the St. Helens zone (SHZ), a 130 km-long zone of moderate magnitude earthquakes (maximum magnitude of 5.5) that strikes north-northwest through Mount St. Helens. Crustal earthquakes are also concentrated in the west Rainier zone about 10 km west of the summit of Mount Rainier and in a broad area southwest of the SHZ toward the Columbia River (Figure 3a). Earthquakes have been located beneath Goat Rocks volcano and at Mount Hood, but there is little seismicity located beneath the regions of extensive late Cenozoic basaltic cover southeast and southwest of Mount Adams (Figure 3a). Earthquake focal mechanisms indicate that horizontal strike-slip faulting on nearly vertical fault planes dominates the region west of the central volcanic arc (Weaver and Malone, 1987). Along the SHZ, most of the focal mechanisms have compressive axes oriented nearly horizontal in the northeast-southwest direction, approximately parallel with the convergence direction between the Juan de Fuca and North American plates.

From the viewpoint of volcano monitoring, the segment of the Cascades from Mount Rainier to Mount Hood shows the close connection between regional seismic zones and the location of the volcanic centres. Mount St. Helens is located on the SHZ and short fault segments that comprise the zone apparently become the bounding faults of the shallow magmatic system beneath the lava dome (Weaver *et al.*, 1987). As earthquakes occur near Mount Hood, evidence is developing that a seismic zone strikes south-

southeast from the summit; focal mechanisms for mainshock-aftershock sequences in 1978 and 1989 indicate right-lateral strike-slip motion along this zone (Weaver *et al.*, 1982). Similarly, shallow (<10 km) right-lateral strike-slip focal mechanisms have been calculated for earthquakes beneath the Pliocene volcanic centre at Goat Rocks; an earthquake of magnitude 5.0 with this mechanism occurred here in 1981. Thus, we characterize this segment as having high rates of background seismicity with events routinely located with magnitudes up to about 3. Superimposed on this background activity are occasional moderate magnitude events (4.0 to at least 5.5); these events can be expected to have aftershock sequences (*e.g.*, Grant *et al.*, 1984) and may occur very close to the major stratovolcanoes (*e.g.*, Crosson and Frank, 1975).

Seismicity of the Mount Shasta-Lassen Peak segment. There are two broad zones of earthquakes within the southern Cascade Range. The first is a nearly north-south striking zone that is spatially located near the western boundary of the Cascades and the eastern boundary of the pre-Cenozoic Klamath Mountains and Great Valley sequence (Figure 3b); these earthquakes typically occur near mid-crustal depths (10-25 km) and have little direct relation to volcanic hazards. The second zone strikes southeast from just north of Lassen Peak toward Lake Almanor (Figure 3b) and continues southeastward along the eastern edge of the northern Sierra Nevada. This zone is truncated north of Mount Lassen by a diffuse, northeasterly striking alignment of earthquakes (Figure 3b); both this northeast striking zone and the southeasterly striking zone passing through Lassen Peak were noted by Klein (1979).

The seismicity distribution changes to the north of the northeasterly striking seismic zone. Few earthquakes are located west of the Cascades within the pre-Cenozoic Klamath Mountains (Figures 2 and 3b) or to the east of the range in the Modoc Plateau (Figure 3b), an area of late Cenozoic Basin and Range-style extension. Within the Cascades proper, despite the presence of many normal faults with Quaternary displacements north of Lassen Peak, relatively few earthquakes occur (Figure 3b). Several earthquake swarms have occurred between Mount Shasta and Medicine Lake Volcano, but seismically defined zones, with lengths greater than a few kilometres, have not yet been identified.

The pattern of seismicity in this segment of the Cascade Range suggests that most of the earthquake activity is a reflection of regional-scale geological structure rather than Quaternary volcanism. Along the prominent seismic zone through Lassen Peak (Figures 2 and 3b), Klein (1979) concluded, on the basis of focal mechanisms, that this is a zone of crustal extension that is probably being driven by northwesterly directed right-lateral shear. Lassen volcanism terminates to the south against the Sierra Nevada batholith; the probable extension of the Sierran basement northward beneath the Lassen volcanic centre is suggested by aeromagnetic data (Blakely *et al.*, 1985) and a seismic refraction profile that strikes across the volcanic cover at Lassen and into the Sierran rocks (Berge and Stauber, 1987). Northwest of the Lassen region, rocks of the Klamath Mountains province crop out in several places and aeromagnetic data have been interpreted to suggest that the basement rocks of the Klamath Mountains continue about as far south beneath the Cascades as the northeast-striking seismic zone (Blakely *et al.*, 1985). Thus, it appears that the seismicity of the Lassen zone is largely reflecting the presence of basement rocks of the Sierra; perhaps the northeast-striking earthquake zone is the northernmost extent of Sierran basement. Near Mount Shasta and Medicine Lake Volcano, seismicity is more typical of Basin and Range activity — earthquake swarms superimposed on a low rate of regional seismicity. Here, the basement rocks do not have an obvious relation to the earthquake distribution.

Seismicity beneath stratovolcanoes. At five stratovolcanoes (mounts Rainier, St. Helens, Hood, and Shasta; also Lassen Peak) the distribution of seismic stations is sufficient that earthquake locations beneath the main vents are well constrained; few earthquakes have been recorded near Mount Shasta. At Mount Rainier, the regional seismic activity is located west of the volcano, but a few earthquakes are located at shallow depths within the upper summit region (Figure 4a). To date, no connection has been identified between the activity to the west and that near the summit, but the summit activity may be related to several possible hazards. First, the events could be related to a shallow magma reservoir within the upper cone of the volcano. Second, they could be part of a fault zone. Or third, they could be related to surficial processes such as the movement of the large glaciers near the summit.

Mount St. Helens, Mount Hood and Lassen Peak are on regional seismic zones, unlike Mount Rainier. Mount St. Helens is located at a point where the SHZ is offset by a few kilometres and changes strike from nearly north-south to the north of the volcano to south-southeast south of the cone (Figure 4b). Within the offset are the thousands of volcanic earthquakes that have accompanied the eruption of Mount St. Helens since 1980. Far fewer events have been recorded at Mount Hood and Lassen Peak (Figures 4c and 4d). Earthquake activity at Mount Hood occurs directly beneath the upper flanks of the volcano; a magnitude 4.0 event occurred here in 1974 (Weaver *et al.*, 1982). The pattern of seismicity at Lassen has changed little since Klein's (1979) summary: very few events occur directly beneath the main dome at Lassen Peak that erupted in 1914-1917 and most occur beneath the geothermal system south of Lassen Peak.

Volcanic Seismicity at Mount St. Helens

Directly beneath Mount St. Helens, thousands of volcanic earthquakes have been located (Figure 4b); Malone (1990) provides

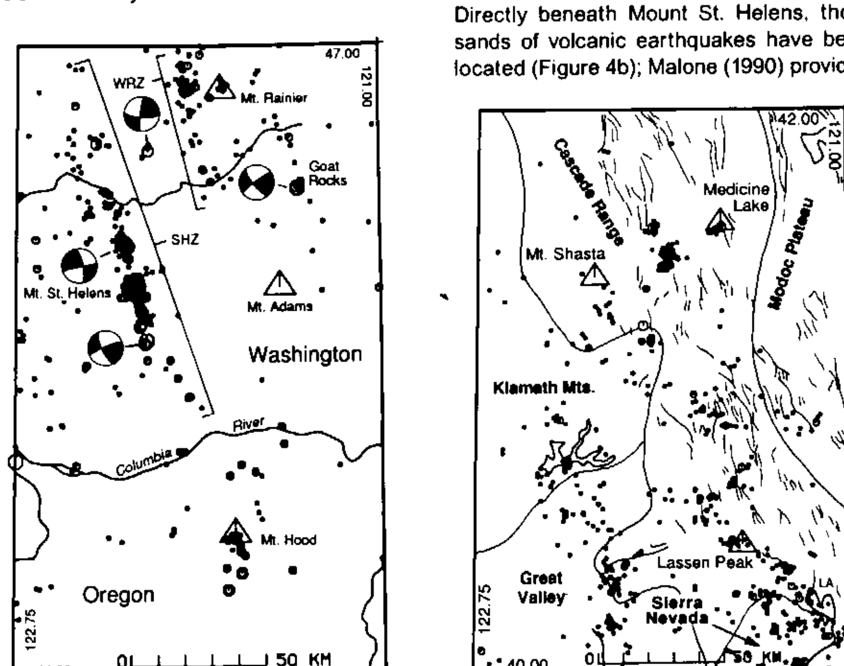

Figure 3 *Seismicity in the Cascade Range:* (**a**) ***(left)*** *Mount Rainier to Mount Hood segment, and* (**b**) ***(right)*** *Mount Shasta to Lassen Peak segment. Earthquakes are scaled as in Figure 2. Earthquake focal mechanisms are shown for earthquakes greater than magnitude 5; mechanism are upper hemisphere with darkened quadrants being compressional and white quadrants dilatational.* ***SHZ*** *and* ***WRZ*** *are discussed in text.* ***LA*** *is Lake Almanor discussed in text. Light lines in 3b are faults with Quaternary displacement taken from Jennings (1975).*

a review of the distribution of these earthquakes. Volcanic seismicity is distinctive in that the coda of the events are dominated by longer periods than usually observed on seismograms from local tectonic earthquakes, the P-wave onset is often very emergent, and it can be difficult to distinguish later phases. Although the actual source of these earthquakes is uncertain, the shallow hypocentral depths and their direct association with magmatic eruptions leave little doubt that they reflect magmatic processes.

At Mount St. Helens, volcanic earthquakes have been divided into subclasses (Malone *et al.*, 1983). Generally, events are classified by their dominant frequency content as observed on helicorder records: low frequency (<2 hz), medium frequency (~2-5 hz), and high frequency (~5-10+ hz). The first two categories are associated with shallow depths that range from essentially the surface of the crater to not more than a few kilometres. The high frequency earthquakes have all of the essential coda characteristics of tectonic earthquakes (P and S waves, impulsive onsets and rapid coda decay) and are located at depths below about 3 km.

Predictions of future eruptive behaviour at Mount St. Helens rely on plotting the seismic energy release from volcanic earthquakes against time and comparing the rate of change of the total energy release with the patterns for past eruptions. Summaries of eruption prediction techniques are available elsewhere (Swanson *et al.*, 1985; Malone *et al.*, 1983). Eruptions at Mount St. Helens have been classified as mainly explosive or dome-building; Swanson *et al.* (1985) provided a review of the eruptive history through 1984. Three dome-building eruptions, one in 1985 and two in 1986, have occurred since their review (Swanson, 1990).

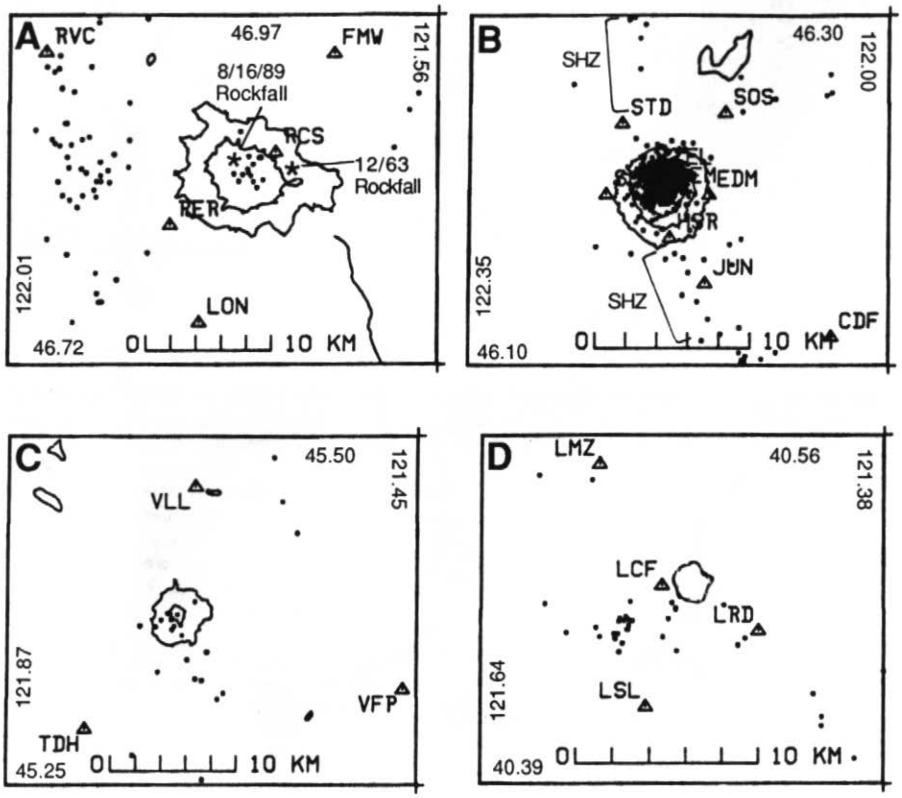

Figure 4 *Seismicity near selected volcanoes:* **(a)** *Mount Rainier,* **(b)** *Mount St. Helens,* **(c)** *Mount Hood, and* **(d)** *Lassen Peak. Earthquakes scaled as in Figure 2. Triangles and letter codes are operating seismic stations. Contours are the 2285 and 3400 metre elevations at Mount Rainier and Mount Hood, 1700 and 2285 metre elevations at Mount St. Helens, and the 3400 metre elevation at Lassen Peak.*

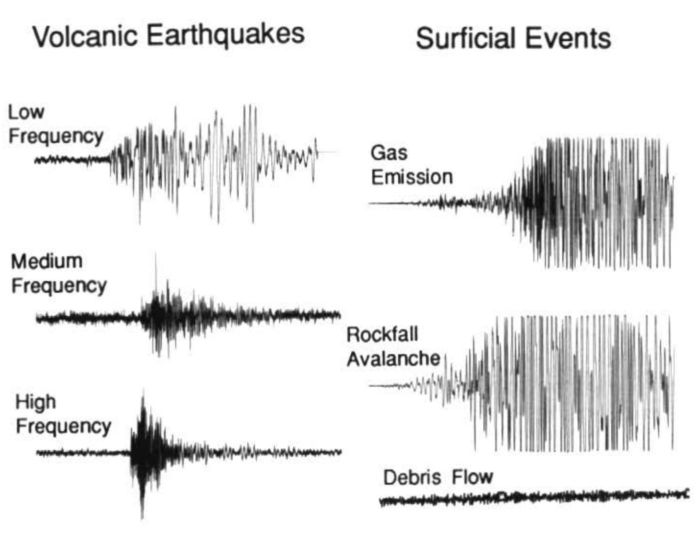

Figure 5 *Example of seismograms of volcanic and surficial events. All of the volcanic events, the gas emission and the rockfall avalanche are from Mount St. Helens; the recording station is about 4 km from all sources. The debris flow is from Mount Rainier, recorded on a station 10 km away from the source. Record length is 90 seconds for all seismograms.*

Surficial Sources

At least four types of surficial sources are known on the northern volcanoes: icequakes, steam emissions, debris flows and falls of rock or ice. Lahars also occur on Mount Shasta and many of the large volcanic cones have potential sources for rockfall. Icequakes have been identified on Mount St. Helens, Mount Rainier and Mount Baker. These signals are similar to low- or medium-frequency volcanic earthquakes. Their sources are within the glaciers and the signals attenuate very rapidly with increasing epicentral distance. Not all glaciers produce icequakes and their source remains problematical. However, they are important for monitoring considerations both because of the large number of events and because in certain circumstances variations in their rate of occurrence may offer warning of an ice-related hazard. In 1976, a rapid increase in the number of icequakes recorded at Mount Baker occurred hours before Sherman Glacier slid on its base into the summit crater area (Weaver and Malone, 1979). And, in 1969, a five-fold increase in glacial events occurred as the portion of the Emmons Glacier above 3000 m on Mount Rainier broke into blocks approximately 100 m on a side.

The last three signal types share a common characteristic of a source extended in time. Gas emissions have occurred repeatedly at Mount St. Helens since the 1980 eruption sequence began. This signal (Figure 5) typically begins with a low amplitude, emergent onset that builds monotonically to higher amplitude. Gas emissions are considered to involve only the most shallow level of the lava dome at Mount St. Helens and often are not preceded by recognizable precursors.

The largest rockfall avalanche in the Cascades since 1960 was that on Little Tahoma, just east of the summit of Mount Rainier, on December 14, 1963. The volume of this avalanche is estimated at 11×10^6 m^3, and the deposits were found up to 7 km down valley (Crandell and Fahnestock, 1965). On August 16, 1989, the largest rockfall avalanche since that on Little Tahoma began near 3400 m elevation on the north side of Mount Rainier (Figure 4a). The avalanche travelled about 4 km downslope and involved about 10^6 m^3 of material. The rockfall generated four discrete seismic signals that saturated the two closest seismograph stations (Figure 4a); the last and largest event was recorded across the seismic network to distances up to 200 km. This complexity suggests that the rockfall occurred as a sequence of failures rather than a single event. One signal was located using standard earthquake location techniques and was constrained to be within 1 km of the seismic station RCS (Figure 4a). Poor weather that day prevented visual confirmation of the rockfall, but officials at Mount Rainier National Park were advised of the event by USGS and University of Washington personnel and checked their records for missing climbers; fortunately there were none. Although not all such events may be precisely locatable, this event was a clear demonstration of the ability to use the seismic network to help mitigate hazards associated with large rockfall avalanches.

Lahars (mudflows and debris flows from volcanoes) occur when a large volume of water is released suddenly and mobilizes loose rock, carrying the debris down valleys. At Mount St. Helens, lahars have been initiated by volcanic explosions that have subsequently caused rapid melting of snow or ice, whereas at Mount Rainier, glacial outburst floods, caused when water stored within a glacier suddenly escapes, have triggered numerous such events. Since 1926, more than 30 debris flows or mudflows have been observed at Mount Rainier and, between 1986 and 1989, more than a dozen were correlated with seismic signals. A typical debris flow or mudflow signal has a very emergent onset and, at Mount Rainier, the average duration is about 20 minutes. Most show a steady increase in amplitude followed by a gradual decrease to background noise. The frequency of the seismic signals is fairly monochromatic at 1-2 Hz as recorded on helicorder by a station 10 km from the source (Figure 5). Debris flow locations can be estimated by comparing relative amplitudes from a minimum of two stations. Currently, only Mount Rainier, Mount St. Helens and Mount Hood are routinely monitored for surficial events; the existing seismic network stations at Mount Shasta and Lassen Peak should allow experimentation to see whether lahars and rockfalls can be seismically detected at these volcanoes.

Discussion

The main lesson from nearly three decades of continuous seismic monitoring is unequivocal and comes from the 1980 experience at Mount St. Helens: shallow volcanic earthquakes signal a serious eruption potential. With respect to tectonic earthquakes, volcano monitoring strategies must take into account the segmentation of the range suggested by the earthquake distribution. In the Mount Rainier to Mount Hood segment, moderate magnitude tectonic earthquakes are expected beneath the volcanoes; however, a moderate magnitude event in the shallow summit region of Mount Rainier could have extremely serious hazard (not necessarily eruptive) implications. At Lassen Peak, there are few earthquakes beneath the vent areas that erupted earlier this century and, echoing Klein (1979), any earthquake here should be viewed with alarm as a possible precursor to volcanic activity. However, at Medicine Lake Volcano, moderate earthquakes have occurred and can be expected directly beneath the volcano; Mount Shasta is probably also subject to infrequent moderate earthquakes. In the segment north of Mount Rainier, very few earthquakes are associated with the volcanoes, but this is also an area with limited volumes of Quaternary volcanism (Sherrod and Smith, in press) and very few hints of late Cenozoic faulting are observed. Here, a moderate magnitude earthquake beneath one of the volcanoes would by itself not be viewed as indicating an immediate volcanic eruption. The most likely response would be to watch for the development of an aftershock sequence (rapid decay in both magnitude and occurrence with time). The segment where the appropriate response to earthquake occurrence is the most uncertain is that between Mount Hood and Mount Shasta. The tectonic setting is poorly known, as this segment has a complicated mixture of both Cascade arc volcanoes and Basin and Range-style basaltic volcanism, and normal faults show late Cenozoic movements. Given the paucity of seismic data here, the complicated and uncertain tectonics, and the mixture of volcanic regimes, we believe that moderate magnitude earthquakes in the Cascades between Mount Hood and Mount Shasta should be viewed as having potentially serious volcanic hazards consequences.

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