Mount St. Helens, the 1980 Re-awakening and Continuing Seismic Activity

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Summary
Mount St. Helens has been seismically monitored since the summer of 1972. Seismic activity recorded during the 1970s by a single station located on the west flank of the volcano was limited to small swarms of high-frequency earthquakes and low-frequency transient signals usually attributed to glacier motion. The first seismic activity that was recognized as being unusual and with possible volcanic significance was a magnitude 4.2 earthquake on the afternoon of March 20, 1980. In retrospect, the initial unusual seismic activity began several days earlier as small, low-frequency earthquakes with seismogram character similar to, but not exactly the same as, the glacier events. Following the March 20 event, earthquake activity rapidly increased over the next five days until on March 26 as many as eight magnitude 4+ earthquakes per hour were occurring. On the next day, phreatic eruptions began. From then until the climactic eruption on May 18, seismic energy release rates remained fairly constant though the number of earthquakes per unit time decreased. During this period, intermittent phreatic eruptions took place as well as continuous deformation of the north flank. The earthquakes were located in a limited volume directly under the volcano at shallow depths and now are interpreted to have been caused by the fracturing and faulting of shallow volcanic rocks as magma was injected into the base of the volcano. The major eruption on May 18 was triggered by one of these earthquakes, which caused a slope failure of the north flank. As this eruption progressed, shallow earthquake activity declined and deeper activity began. These deeper earthquakes outline the magma conduit system indicating the presence of a small crustal magma reservoir at a depth of 7 to 12 km. Shallow seismicity preceding subsequent eruptions provided data to help with the prediction of most of these eruptions. Deeper seismicity has not been as obviously related to individual eruptions. We speculate that it reflects adjustments in the magma chamber and conduit system, due, in different cases, to a reduction or increase in magma pressure.

Introduction
Routine seismic monitoring of volcanoes in Washington State began in 1972 with the installation of single telemetered seismic stations on each of Mount Baker, Mount Rainier and Mount St. Helens. For the remainder of the 1970s, minor seismic activity was recorded at Mount Rainier and Mount St. Helens. Mount Baker remained remarkably aseismic; even during and after a large change in the thermal emission from the Sherman Crater in 1975 (Malone and Frank, 1975). Studies of the seismic events at Mount Rainier and Mount St. Helens generally concluded that most, if not all, of the shallow low-frequency earthquakes local to each mountain were due to noise generated by glacier motion (Weaver and Malone, 1976).

On the afternoon of March 20, 1980, a large seismic event occurred at Mount St. Helens which was easily recognized as not being due to ice or glacier motion. This magnitude 4.2 earthquake began a remarkable sequence of earthquakes which culminated in the climactic eruption of May 18. In this paper, I review the time sequence of events taking place in the spring of 1980, concentrating on the seismic record. The earthquakes and eruptions in the decade following 1980 are of interest in comparison to the early activity. I also discuss some of the constraints that the seismic data place on models for the movement and storage of magma in the plumbing system at Mount St. Helens.

Precursors to the May 18, 1980 Eruption
Changes in seismic activity over the period March 20 to May 18, 1980, were both dramatic and subtle. During the first week of activity, the seismograms for the station SHW, located on the west flank of the volcano at an elevation of 1.4 km, went from showing a few small earthquakes to being totally saturated by continuous shaking and thus virtually useless. Phreatic eruptions from the summit crater began on March 27, one week after the first significant earthquake, and continued off and on for several weeks. Significant deformation of the north side of the mountain was recognized in early April, and this deformation continued in a remarkably uniform way up to the eruption on May 18. While the mountain was being carefully monitored by a host of investigators, in retrospect no changes in the monitored data could have been used to predict the time or size of the resulting eruption. Details of the various monitoring efforts and their results are thoroughly covered in numerous articles in Lipman and Mullineaux (1981).

Earthquake Locations. Within 28 hours of the first large earthquake of the sequence, four new seismic stations were installed in the Mount St. Helens area, and 11 stations were operating by March 30. These seismic stations provided arrival time data which allowed hypocentres to be calculated. Locations for about 900 of the several thousand recorded earthquakes were calculated using a one-dimensional velocity model and station corrections determined by an inversion of arrival times from a selected subset of well-recorded earthquakes and artificial explosions (Malone and Pavlis, 1983). The vast majority of the determined hypocentres were shallow (< 3 km), directly under the mountain. Because the first arrivals were emergent and difficult to time accurately, focal depths in the complex velocity structure are poorly resolved. The depth resolution for these shallow events is no better than ±2 km. The depths determined by our standard location procedures were almost always constrained to the datum reference plane, which is the average elevation of the local seismic stations (1.1 km above sea level). It is quite possible or even likely that most of these earthquakes have hypocentres within the mountain above the reference datum. I feel that the majority of the earthquakes, and all of the larger events, occurred within a 3-km-diameter volume centred in the volcano.

During the initial analysis of the pre-May 18 seismic sequence, the large shallow earthquakes monopolized our analysis resources because they seemed to be the largest and most important events. Later, it was discovered that numerous deeper, though much smaller, earthquakes also occurred, whose signals were not so easy to detect in the midst of many large earthquakes. Jonientz-Trisler and Zollweg (1987) reported the identification and analysis of a number of these events, which they locate from 4 to 14 km below the mountain. These events fall into narrow zones descending vertically under the mountain from 5 to 7 km and then dip off to the east-northeast from 7 to 11 km. They suggest these earthquakes "represent regions of brittle failure surrounding a narrow conduit system through which magma was injected prior to the eruption". These small, deep earthquakes produced high-frequency seismograms with characteristics similar to earthquakes that followed the main explosive eruptions of 1980.

Earthquake Time Sequence. Figure 1 shows several time plots of the seismic sequence leading up to the May 18 climactic eruption. The top of this figure shows the depths of located earthquakes and the bottom shows the earthquake rate based on a ***count-log*** produced by reviewing visual drum records for several of the seismic stations that were running continuously during this period. The time, duration, and maximum trace amplitude for each earthquake was determined and entered into the ***count-***

log with a code for the type of event based on its signal character. A magnitude for each earthquake was estimated using a calibration of duration *versus* Wood-Anderson local magnitude determined by Endo *et al.* (1981) and seismic moment was then determined from the moment-magnitude relation:
$\log M_o = 1.4\, M_c + 17$.

In reviewing film records for the SHW station for the period March 1-22, Endo *et al.* (1981) note a slight increase in very small earthquakes beginning about March 16. The inset on the left side of Figure 1 shows the cumulative count and moment release of all the earthquakes detectable on the SHW film records for the period March 12-22. The rate of activity for the early small earthquakes was fairly constant at about 25 events per day between March 16 and 20. After the M=4.2 earthquake at 2347 Universal Time (UT) on March 20, moderate activity continued at a rate of about 60 events per day for two more days and then increased dramatically in both size and number of events. By March 24, the rate was up to almost 500 events per day and, on March 25, the SHW records essentially saturated at 700 events per day. As many as 30 M=4 earthquakes occurred between March 25 and 26. Earthquakes with a magnitude less than about 2.6 were no longer counted after March 24 and, thus, the cumulative total of 3500 events for the whole sequence is a minimum since it does not include numerous small earthquakes.

After the first steam explosion at about 2030 (UT) on March 27, the rate of seismicity declined to about 200 events per day; however, the average background noise level on the SHW records remained so high that most smaller earthquakes were obscured and not countable. Seismic activity continued at a high rate from then until the climactic eruption on May 18. Periodic bursts of strong volcanic tremor occurred during early April and early May. This tremor was usually quite monochromatic (harmonic tremor) and was strong enough to be recorded on seismographs 100 km away.

While no dramatic changes were noted in the character or pattern of earthquake activity, a few subtle evolutionary changes were observed. Earthquake rate seemed to decrease with time, particularly over the first few weeks. At the same time, the average earthquake size increased. Thus, the seismic moment release per unit time stayed fairly constant over the whole period. About May 7, a very slight increase in the earthquake rate was noted and also a few of the earthquakes were quite large, about M=5. Subtle changes in these parameters were pointed out by Qamar *et al.* (1983). None of these changes were significant enough to indicate the coming major eruption. Even in retrospect, there would have been no way to anticipate the precise time of the final, devastating eruption.

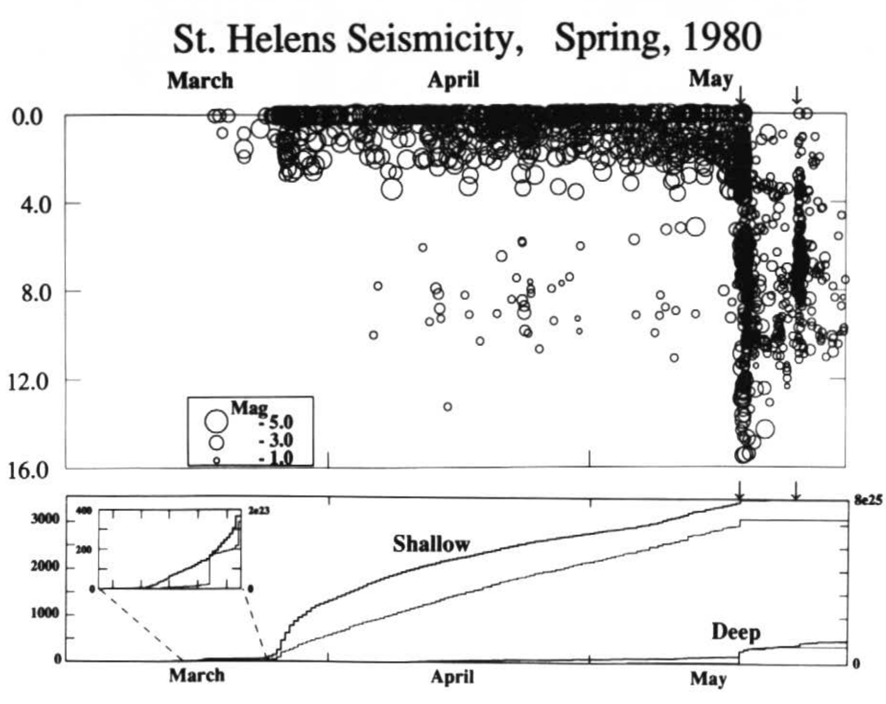

Figure 1 *Time plot for the period March 1 to May 31, 1980. Top section is a time versus depth (in km) plot including all located earthquakes directly under Mount St. Helens from the University of Washington catalogue, scaled by magnitude, and a subset of deep earthquakes between April 5 and May 18 determined by Jonientz-Trisler and Zollweg (1987). The arrows indicate the times of the first steam explosion and the major eruptions. The lower plot shows the cumulative number of earthquakes (thick lines with scales on the left) and cumulative seismic moment release (thin lines with scales on right in dyn-cm) derived from the* ***count-logs*** *produced by reviewing continuous visual drum records of several nearby seismic stations. The deep earthquakes were separated from the shallow ones by seismogram character and are plotted at 10 times their actual values. The inset on the left is a detail of the period, March 16-22, for which all detectable earthquakes were counted rather than just those larger than M=2.5 as were counted for the whole period.*

The total cumulative seismic moment for the sequence of shallow earthquakes between March 20 and May 18 calculated from this data set is 6.4×10^{25} *dyn-cm*. This is in contrast to the total cumulative moment of the deeper, high-frequency earthquakes up to May 18 of only 5.0×10^{20} *dyn-cm*, five orders of magnitude less. Following the May 18 eruption, as well as later explosive eruptions, the rate of larger, deep, high-frequency earthquakes increased. Still, their total cumulative seismic moment is only 7.3×10^{23} *dyn-cm*, a fraction of that for the shallow precursory sequence.

Volcanic Activity. The first surface manifestations of volcanic activity took place on March 27 when a steam explosion, or phreatic eruption, blew a hole in the snow-covered summit crater. For the following several weeks, phreatic eruptions were common, some lasting for only a few minutes, others for many hours. They created two craters in the summit of the mountain which eventually coalesced into one crater that gradually enlarged to about 300 m across and 150 m deep. These phreatic eruptions had no identifiable seismic activity associated with them. They ceased in mid-April, but began again in early May.

Deformation. At about the same time as the peak in earthquake activity and the first phreatic eruption in late March, deformation began high on the north slope and in the summit area of the mountain. In early April, a bulge or zone of high deformation was identified and its development was measured by geodetic techniques (Lipman *et al.*, 1981). A section of the north flank about 1.5 km across by 2 km long was gradually and continually being displaced northward. The rate of displacement was a remarkably steady 1.4 m per day. While no obvious changes in the rate of displacement were associated with earthquake activity, the deformation data, usually taken at intervals of several days between readings, are not ideal for this sort of comparison. A comparison between one deformation line measured repeatedly over an eight-hour period and the seismic record shows only a very questionable temporal association between changes in line length and earthquakes. However, Lipman *et al.* (1981) state that, because of differences in the average long-term deformation rate and that measured during the eight-hour period, it "remains very possible that abrupt deformations associated with bursts of seismic energy accounted for part of the cumulative total displacement".

Seismicity Following May 18, 1980

The character of the seismicity, deformation and eruption patterns changed completely following the climactic eruption on May 18. Subsequent eruptions were no longer phreatic, but rather involved juvenile material in the form of ash, pyroclastic flows and lava. Significant deformation was limited to the interior of the newly formed crater and lava dome. The large, low-frequency earthquakes common before May 18 ceased, being replaced by much smaller and deeper, high-frequency earthquakes that rapidly died out after each explosive eruption. Subsequent eruptions were preceded by distinct and easily recognized changes in seismicity and deformation. Increases in volcanic tremor level preceded by several hours three explosive eruptions in the summer of 1980 when no lava dome was present in the crater. Increases in the number and size of shallow, low-frequency volcanic earthquakes preceded two explosive eruptions in 1980 and almost all of the dome-building eruptions of 1981 through 1986 (Malone *et al.*, 1981; Malone and Pavlis, 1983). The real-time analysis of the seismic data and the deformation record allowed for the prediction of almost all of these eruptions hours to many days ahead of each (Swanson *et al.*, 1983).

Figure 2 summarizes the seismic record for Mount St. Helens from 1980 through May 1, 1990. These plots are from the University of Washington catalogue of located earthquakes. Not all earthquakes at Mount St. Helens make it into the catalogue. During the spring of 1980 and also during seismic precursors to later eruptions, the earthquake rates were so high that only the larger events were processed. The 7,355 earthquakes in the catalogue, and shown here, contrast with the almost 27,000 earthquakes in our ***count-logs*** for the same period. Since the large events contribute most to the seismic moment rate curves, these curves will not be much in error because of missing many smaller events.

The vast majority of the located earthquakes and moment release occur in the shallow crust or within the volcanic edifice. For almost every eruption, a peak in the shallow seismicity is noted. The three explosive eruptions in the summer of 1980, for which no dome was present in the crater, are the exception. In almost every case where a dome was present, shallow earthquakes preceded and accompanied eruptions, and during the later eruptions when the dome had grown quite large, the precursory earthquake swarms became quite energetic.

A comparison of depths and event rates with time is interesting (Figure 2). While most eruptions are preceded by numerous shallow earthquakes, the pattern for the deeper events is not so clear. Just following the explosive eruptions of 1980, deep seismicity was common. Many deep events preceded the minor explosive eruption of March, 1982; however, they were so small that they did not contribute significantly to the moment rate plot. Note that for the deep earthquakes following the early explosive eruptions, there is a hiatus of events between 4 and 6 km and then a concentration from 6 to 11 km, with a few larger events extending below that. The deep earthquakes prior to the March and August 1982 eruptions are concentrated between 4 and 8 km. Few deep earthquakes were associated with the non-explosive dome-building eruptions of 1981 to 1986. However, since mid-1987, an increasing number of these deeper earthquakes have seemed to concentrate in the 4-8 km deep zone. They often occur in swarms lasting for several days to over a week, the largest included 158 earthquakes during October 18-31, 1989.

Magma System Model

Mount St. Helens' eruptive history includes major eruptive periods every few centuries (Crandell *et al.*, 1975). A question addressed here regards the nature of the magma supply system. Is each eruptive period preceded and perhaps triggered by a major batch of new magma rising from great depths to a shallow system from which it erupts, or does magma trickle relatively constantly into the shallow system, which stores the magma for decades or centuries before erupting? The seismic activity at St. Helens over the past two decades can shed light on this question.

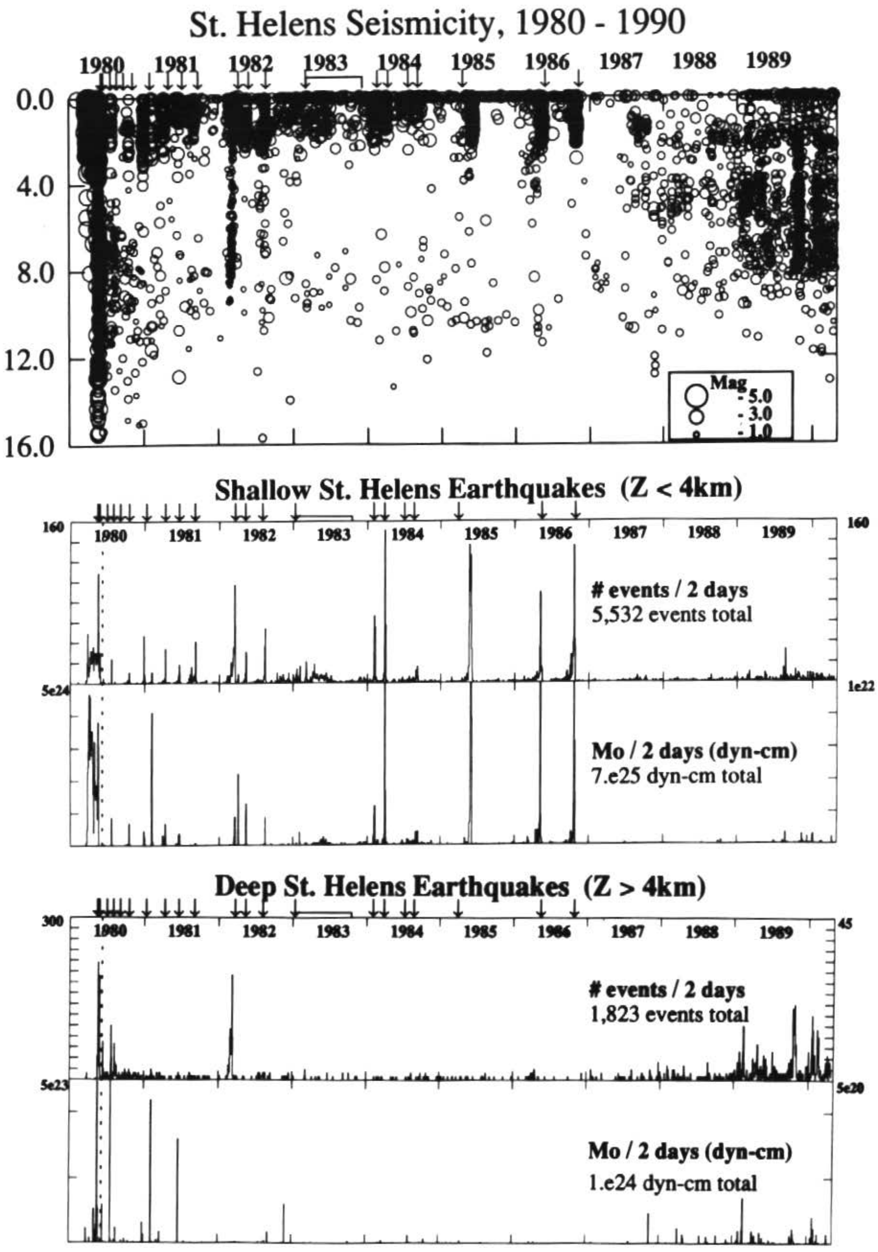

Figure 2 *Time plots of Mount St. Helens seismicity for the decade from Jan. 1, 1980, to May 1, 1990. The upper plot is similar to Figure 1. The lower plots show numbers of events and moment release per two-day interval divided into two depth ranges. The scales on the left are for the period before June 1, 1980 (shown as vertical dashed line) and scales on the right are after June 1, 1980. Data are from University of Washington catalogue of located events.*

A model that is likely supported by the seismicity involves a low, but relatively continuous, supply of magma from a deep source rising into a crustal magma chamber where it accumulates. Pressure eventually builds high enough to force magma to the surface.

The magma plumbing system may be divided into four zones: (1) the deep zone, which starts at the magma source, presumably the subducting Juan de Fuca slab, and reaches up to depths of about 12 km; (2) the crustal magma chamber which lies at depths between 12 and about 7 km; (3) the shallow conduit which extends from the top of the magma chamber at 7 km to near the surface; and (4) the vent system, which may be open, may have a young dome plugging it, or may have old domes or flows obscuring its presence as before May 18, 1980 (see Figure 3).

The deep zone is the most elusive since little direct evidence indicates its existence or nature. Magma must come from depth into the crust through conduits or zones of weakness. Weaver *et al.* (1987) suggest that the St. Helens seismic zone, a 60 km-long feature outlined by seismic activity (Weaver *et al.*, 1990), has an offset in its NNW-SSE trend providing a localized zone of tension or rifting directly under Mount St. Helens. The earthquakes in this zone have depths ranging from 10 to 20 km with a few slightly deeper. During and immediately following the May 18 eruption a swarm of earthquakes took place between depths of 12 and 22 km with strike-slip focal mechanisms similar to earthquakes all along the St. Helens seismic zone.

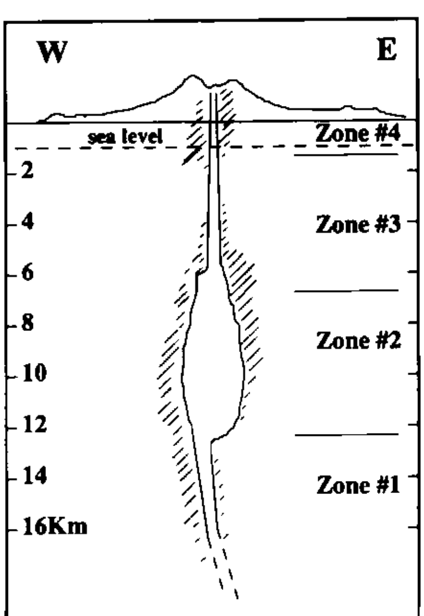

Figure 3 *Cartoon cross-section of hypothesized Mount St. Helens magma plumbing system. Hatched area indicates the zones where most of the earthquakes are. The datum level is 1.1 km above sea level, the average elevation of the local seismograph stations.*

The distribution of hypocentres and their focal mechanisms in zone #2 (from 7 to 12 km) are quite different from those in the deep zone. The earthquake foci are grouped on either side of, and surround, an earthquake-free volume which has been suggested as the location of a crustal magma chamber (Scandone and Malone, 1985; Shemeta and Weaver, 1986). Focal mechanisms for many of these events as well as their locations are consistent with a vertical cylindrical magma chamber with a diameter of about 1.5 km situated about 600 m north of the current dome. A pressure drop within this chamber during explosive eruptions perturbs the regional stress field, causing a swarm of readjustment earthquakes in the surrounding brittle rock (Barker and Malone, in prep.).

In zone #3, the zone above the magma chamber, the seismicity is more laterally restricted and has a different time history than that of zone #2. Following the explosive eruptions of 1980, relatively few foci fell in this zone; however, during the May 18 eruption, before the minor explosive eruptions of 1982, and during the past three years, an increased number of earthquakes occurred in the 3 to 8 km depth range. Shemeta and Weaver (1986) located a number of earthquakes in this zone during the May 18 eruption and interpreted them to have been caused by the rapid movement of magma up out of the magma chamber and into the conduit. These earthquakes occur near the top of the magma chamber and around the conduit extending up to the base of the volcano. These earthquakes may occur in response to increasing pressures in the upper part of the magma system, as opposed to a pressure decrease causing the earthquakes in zone #2. Because the earthquakes in this zone are small, shallow and not well recorded, it is difficult to determine focal mechanisms for them. Moran and Malone (1989) compared the seismograms of some of these events with earthquakes recorded on the SHW film records from the 1970s and concluded that many of the high-frequency events occurring in swarms during the early- to mid-1970s have a similar character to those now occurring in zone #3.

The vast majority of the earthquakes at Mount St. Helens occur in zone #4, the vent system. These earthquakes almost exclusively occur just before eruptions, but only when an obvious dome blocks the vent. For three eruptions in 1980, only moderate volcanic tremor preceded the eruption outbursts. In each of these cases, no dome was visible in the crater. Almost always where a dome was present, earthquakes in this vent zone preceded an outbreak. The duration and intensity of the precursory earthquake swarm are, at least qualitatively, proportional to the size and apparent stability of the dome. This includes the pre-May 18 seismic sequence for which the summit dome and Goat Rocks dome were blocking the vent system, having been emplaced 400 and 130 years ago, respectively. Precursory seismic sequences take place only in previously erupted volcanic rocks which fail easily under the rapid strains of magma injection. The bulging of the north flank prior to May 18 and the deformation of the dome and crater floor measured before later eruptions are direct surface manifestations of the earthquakes just below. One can use the cumulative seismic moment for the pre-May 18 earthquake sequence to calculate an equivalent displacement on a fault which could be related to the development of the bulge. Using

$$D = M_o \mu A ,$$

where μ is the rigidity (1×10^{11} *dyn/cm*^{2} for volcanic dome rocks) and A is the surface area of the equivalent fault, chosen to be the current surface area of the horseshoe-shaped crater created in the debris flow avalanche and eruption of May 18 ($\sim3\times10^{21}$ *cm*^{2}), a total displacement of 110 m is calculated. This is a significant portion of the 150 m maximum displacement reported by Lipman *et al.* (1981), thus supporting their speculation that abrupt deformation accompanied individual earthquakes.

Conclusions

The four zones in this model have four different types of earthquake sequences associated with them. Seismicity in zone #1, the deep zone, is mostly related to the regional or tectonic environment, though rapid pressure changes in the magma system can trigger earthquakes in this zone. In general, magma moves through this zone slowly, and perhaps continuously, but causes little to no seismicity. Magma trickles into the magma chamber of zone #2, around which earthquakes occur primarily during and after rapid drops in pressure due to large eruptions. The top of this zone is a transition into zone #3, a narrow conduit which leads to the base of the volcano. Earthquakes in this zone are mostly small and are primarily due to increases in pressure at the top of the magma chamber and the conduit. Zone #4 is made up only of low-strength volcanic rocks which fracture as magma arrives from the conduit beneath it, producing large low-frequency volcanic earthquakes as precursors to eruptions. If this model is correct, the recent increasing numbers of small earthquakes in zone #3 indicate that the current eruptive period of Mount St. Helens is not yet finished and stresses are currently increasing in the top of the magma chamber and conduit.

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The Rockslide – Debris Avalanche of the May 18, 1980, Eruption of Mount St. Helens — 10th Anniversary Perspectives

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Summary

The massive rockslide-debris avalanche of the May 18, 1980, eruption of Mount St. Helens began with a retrogressive failure triggered by the 08:32 PDT earthquake. It depressurized the volcano's magmatic and hydrothermal system and produced a hummocky deposit with a volume of 2.5 km^3. Detailed work provides a comprehensive understanding of a previously poorly understood type of event.

The deposit consists of relatively intact pieces (block facies) of the pre-1980 mountain and mixed material (mixed facies) that is primarily rocks from the pre-1980 Mount St. Helens and the 1980 cryptodome. Travel paths of rockslide blocks are interpreted from a geologic map of the deposit. The material was fractured and dilated during the rockslide, after which grain-to-grain dispersive stress facilitated flow. During transport, the dilated material mixed but significant fine material was not produced.

Introduction

One of the most important events of the May 18, 1980, eruption of Mount St. Helens was the rockslide-debris avalanche. The rockslide was triggered by a M=5.1 earthquake at 08:32 PDT, which depressurized the volcano's magmatic and hydrothermal system, resulting in the lateral blast. Eyewitness photographs document that the rockslide began with detachment of at least three slide blocks which accelerated to a maximum of 70 m•s^{-1}. The slide blocks broke up into smaller pieces to become a flowing debris avalanche, moving at an average rate of 35 m•s^{-1} (Voight, 1981; Voight *et al.*, 1983). The resulting hummocky deposit has a volume of 2.5 km^3 (Figure 1). The Mount St. Helens rockslide-debris avalanche is the largest known mass movement in historic times.

In the ten years since the eruption, detailed field, laboratory, and modelling work has provided a comprehensive understanding of a previously poorly-understood type of event. The work includes analyses of the eyewitness photographs (Voight, 1981), the stability of the pre-eruption mountain (Voight *et al.*, 1983), the geology and emplacement of the deposit (Glicken, 1986, in press-a), the stability of debris-avalanche dams formed by the deposit (Glicken *et al.*, 1989a; Glicken and Voight, In press; Meyer *et al.*, 1985; Meyer *et al.*, 1986) and microscopic characteristics of the deposit with implications for particle-particle interactions (Glicken *et al.*, 1989b). Results of the Mount St. Helens work continue to be applied to the study of volcanic debris avalanches, associated eruptions, and hazards around the world (*e.g.*, Boudon *et al.*, 1987; summarized in Siebert *et al.*, 1987).

Stability Model

A static mathematical model of the stability of the pre-eruption mountain indicates that the mountain was stable under reasonable assumptions of cohesion and water table conditions (Voight *et al.*, 1983). Reduction of cohesion, resulting primarily from intrusion of the March-May 1980 cryptodome and associated hydrothermal fluids, and dynamic loading resulting from the M=5.1 earthquake were required for failure.

Composition of the Deposit

To analyze the debris avalanche deposit, it is necessary to define terms rigorously (Glicken, in press-b). Two different kinds of particles compose the deposit: clasts, which are rocks that would not break if passed through a sieve or immersed in water (hard rocks), and debris-avalanche blocks, which are unconsolidated or semi-consolidated (relatively soft) pieces of the pre-1980 mountain transported relatively intact. The parts of the deposit composed of debris-avalanche blocks are called block facies; the parts of the deposit composed of a blended mix of rock types from the pre-1980 mountain, juvenile material (cryptodome) and, locally, material from the underlying terrain are called mixed facies (previously referred to as matrix facies; *e.g.*, Ui, 1983).

In debris-avalanche blocks (debris blocks for brevity), recognizable structures or stratigraphy preserved from the pre-eruption Mount St. Helens are locally present (Figure 2). However, the clasts within the debris blocks are shattered, so the deposit is finer grained than the comparable material of the pre-1980 mountain.

The eastern half of the deposit is composed almost entirely of block facies (Figures 1 and 4), while the western part consists of primarily mixed facies with some debris