Reports

Predicting Eruptions at Mount St. Helens, June 1980 Through December 1982

Abstract. *Thirteen eruptions of Mount St. Helens between June 1980 and December 1982 were predicted tens of minutes to, more generally, a few hours in advance. The last seven of these eruptions, starting with that of mid-April 1981, were predicted between 3 days and 3 weeks in advance. Precursory seismicity, deformation of the crater floor and the lava dome, and, to a lesser extent, gas emissions provided telltale evidence of forthcoming eruptions. The newly developed capability for prediction reduced risk to life and property and influenced land-use decisions.*

In the period beginning after the catastrophic eruption of 18 May 1980 and the smaller eruption a week later (*1*), 13 eruptions (Table 1) occurred at Mount St. Helens before the end of 1982 and more are likely. Recent eruptions have been relatively minor; no large explosive event has occurred since October 1980. The eruptions that were predominantly explosive generated both tephra (volcanic ash) plumes thousands of meters high and pyroclastic flows that traveled 6 to 9 km from the vent. A dome (Fig. 1) grew in the crater after explosive eruptions in June, August, and October 1980. Each eruption since then has added small (1×10^6 to 4×10^6 m^3) flows or lobes of dacite lava to the surface of the composite dome. Before eruptions, the dome inflates as a result of the intrusion of magma; this process accounts for 10 to 20 percent of the dome's volume. By January 1983, the dome was about 600 m long, 500 m wide (not including flanking talus), and 205 m high, and its volume was more than 30×10^6 m^3.

Predictions. Intermittent volcanism at Mount St. Helens since 18 May 1980 has provided an unusual opportunity to devise and test methods for predicting eruptions. The 25 May 1980 eruption was not predicted, but the 13 subsequent eruptions in 1980 through 1982 were predicted tens of minutes to, more generally, a few hours in advance. The last seven of these eruptions, starting with that of mid-April 1981, were also predicted between 3 days and 3 weeks in advance. No predictions of eruptions that failed to occur were issued. Such repeated accuracy is uncommon if not unparalleled in volcanology (Table 1).

The success of predictions at Mount St. Helens was made possible by a favorable combination of characteristics lacking at many other active volcanoes: processes act repeatedly on viscous magma beneath a single, readily accessible vent area. The high viscosity of the magma favors the relatively slow development of precursors, and that slowness makes their recognition and measurement possible. In addition, considerable personnel and financial resources have been committed to the study, and several monitoring techniques have been applied.

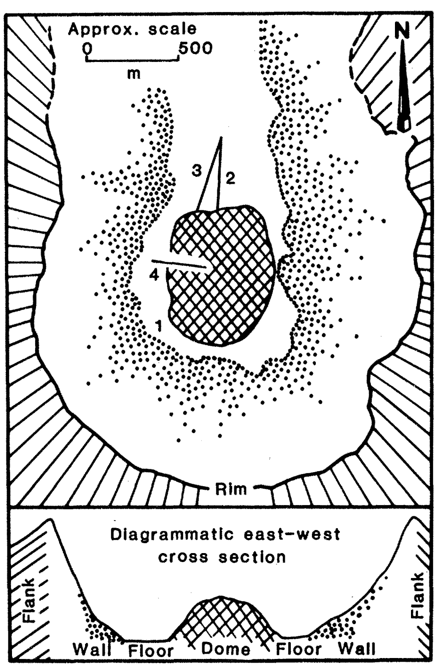


Fig. 1. Sketch map and cross section of the Mount St. Helens crater at the end of 1982; stippling indicates talus; crosshatching designates the lava dome and flanking talus cones. Numbers are identified in Figs. 2 through 5: 1, Christina 2 thrust fault; 2, measured slope distance from Hot Spot on crater floor to target Deloris on dome; 3, measured slope distance from Hot Spot on crater floor to target West Dome; 4, measured slope distance from station Don's Place on crater floor to target Near Miss 3 on dome. Instrument station Harry's Ridge is located 8.5 km north of the dome.

We consider here only scientific predictions, those based on repeated objective measurements, either by visual or instrumental means, of ongoing changes at the volcano. Thus, precursory activity of some kind is a prerequisite for scientific prediction. Seers or attention seekers may make predictions, but these are neither scientific nor objective.

We use the term "eruption prediction" more precisely than is common in volcanology. An eruption prediction should state the following:

1) *Place*. It should cite a location on the volcano, not simply "the volcano."

2) *Time*. This means designating a reasonably short period within which the eruption is expected. As the eruption nears and more information is obtained, this period—the predictive window—should narrow. At Mount St. Helens, the time period typically narrows from 2 to 3 weeks to a few hours.

3) *Type and magnitude of the eruption*. The prediction should specify whether the eruption is likely to be explosive or nonexplosive, large or small. This is the most difficult requirement to meet at Mount St. Helens, for we are uncertain whether recognized precursors necessarily reflect the type and magnitude of the future eruption.

An ideal prediction should also include a statement of the likelihood of each part of the prediction. At present, the likelihood that the prediction is precisely accurate decreases from factor 1 to factor 3. We do not include numerical estimates of probability in our predictions, but we endeavor to ensure that the likelihood of correctness is high for each factor, as evaluated from our past experience and hypotheses about the volcano, before we issue a prediction.

Predictions of eruptions at Mount St. Helens reduce risk to life and property, ease the concern of people living near the volcano, allow timely evacuation, and give help in land-use decisions. To achieve these benefits, predictions must be accurate; repeated inaccurate predictions encourage popular distrust and may be more harmful than no predictions at all.

Predictions also test hypotheses concerning volcanic processes. An accurate

Table 1. Chronology of eruptions, forecasts, and predictions at Mount St. Helens from 25 May 1980 to the end of 1982. Parentheses are used to indicate criteria of lesser importance. Abbreviations: EA, explosive activity; DB, dome-building activity; S, seismicity; G, gas; CT, crater tilt; CF, crater-floor deformation; DD, dome deformation; CD, cone deformation; H, stratigraphic and historic records; E, the previous few eruptions.

Eruption start		Eruption type	Forecast			Relatively long-term prediction			Relative short-term prediction			
Date	Time (local)		Date	Interval	Basis	Date	Predictive window	Basis	Date	Time (local)	Predictive window	Basis
						1980						
5/25	0236	EA							Not predicted			
			5/26	Weeks to months	E,H							
			6/1	Weeks to months	E,H							
6/12	2111	EA and DB							6/12†	1800	Soon	
			7/1	Weeks to months	E,H							
7/22	1714	EA							7/22†	1040	Few hours	S
8/7	1623	EA and DB							8/7†	1227	Few hours	S,(G)
			9/1	Weeks to months	E,H							
10/16	2158	EA and DB							10/16†	2026	Few hours	S
			11/15	Weeks to months								
									12/25†	1850	1 to 2 days	S
12/27	?	DB							12/27	1520	Very soon	S
						1981						
			2/2	Weeks to months	E,H							
									2/4	2400	Soon	S,(CF)
2/5	a.m.	DB*							2/5	0400	12 hours	S
			3/27	Weeks to months	CD,S,G,E							
						3/30	2 weeks	CF,(S)				
									4/9	2300	24 hours	S
4/10	0821	DB*							4/10	0630	This morning	S
						6/12	2 weeks	CF,(G)				
									6/18	1100	1 to 2 days	S,CF,(G)
6/18	2400	DB*							6/18	1715	12 hours	S,CT
			8/5	Weeks to months	CD,S,G,E							
						8/26	2 weeks from 9/2	CF,(G)				
									9/6	0800	12 to 48 hours	S,CF
9/6	Late p.m.	DB							9/6	1330	12 hours	S,CT
						10/24	2 weeks	CF				
10/30	p.m.	DB*							10/30	1100	24 hours	S,CT
						1982						
						3/12	3 weeks	DD,(CF)				
						3/15	1 to 5 days	DD,CF				
3/19 (continued until 4/12)	1927	EA (minor) and DB							3/19	0900	24 hours	S,(DD,CF)
						3/24	(Not over yet)	DD,G				
						5/11	Next week, possibly next few days	DD,(S)				
									5/13	2300	36 hours, possibly 12 hours	S
5/14	1100?	DB*										
						7/30	3 weeks	S,DD,CF				
						8/16	4 days, possibly next 2 days	DD,CF,S				
									8/17	0655	24 hours	S,DD,CF
8/18	1030?	DB							8/18	0745	Soon; endogenous growth under way	S,DD,CF

*Small tephra-laden plumes accompanied start of extrusion. †Verbal communications to the Forest Service and State Department of Emergency Services; written predictions not initiated until 27 December 1980.

prediction is necessary but insufficient evidence for the hypothesis on which the prediction was based. An incorrect prediction challenges the volcanologist and so may lead to improved hypotheses.

An eruption prediction should be understandable if it is to be useful for nonscientists. In issuing timely predictions, it may be necessary to balance a public official's need to know against a volcanologist's need for more data. Thus far, this has not been a major point of contention at Mount St. Helens. We do not release a prediction until precursory data show a well-defined trend. At those times when a public statement seems warranted before we can make a prediction, we issue a factual statement describing the present situation.

We issue predictions at Mount St. Helens in two stages, depending on the kind of data. Relatively long-term predictions, based primarily on geodetic measurements of ground deformation, are issued from several days to 2 to 4 weeks in advance. Relatively short-term predictions, based primarily on telemetered seismic and tilt data, are made within 1 to 2 days of the anticipated eruption. The two stages overlap in the period of about 2 to 4 days, when seismic and deformation data are of similar importance. In practice, the two stages of predictions are revised to greater precision as the impending eruption draws closer.

An important consideration in eruption prediction is the degree to which the prediction is based on probabilistic or causal (deterministic) factors. All predictive statements are ultimately statements of probability; any statement about the future could be wrong. But predictions based on knowledge or reasonable inference of causes are more likely to be correct than purely probabilistic predictions based solely on pattern recognition. Predictions at Mount St. Helens are becoming increasingly deterministic as we develop hypotheses about the volcano's dynamics. One of our major goals is to improve our knowledge of causes so that predictions become still more deterministic.

Forecasts. Volcanologists frequently must make a forecast, a statement concerning future eruptive activity that cannot be as precise as a prediction. We recognize two types of forecasts at Mount St. Helens. One type is based on the projection of past geologic and geophysical records months to decades in advance. For example, stratigraphic studies conducted between 1960 and 1975 (*2*) showed that Mount St. Helens had erupted frequently and explosively in the recent geologic past and were interpreted to suggest that it "will erupt again, perhaps before the end of this century" (*3*, p. 438). This statement was geologically sound and has proved prescient, but it specified neither the type of activity nor the time precisely. We now use knowledge of the history of Mount St. Helens together with various measures of ongoing activity to forecast activity over the next months to few years (Table 1).

Another type of forecast is made when restlessness at a volcano is recognized but not understood well enough to permit a formal prediction. For example, no prediction was issued during the 2 months before the 18 May 1980 eruption, despite severe ground deformation and intense seismicity, because scientists were uncertain of the outcome. Instead, several forecasts presented a variety of scenarios encompassing a spectrum of diverse possibilities; each scenario was developed on the basis of what had happened in the past at Mount St. Helens or at some other volcano. These forecasts had great societal benefit; without them, many more lives would have been lost on 18 May. Even if we had known then what we know now, however, we could not have "predicted" that eruption (*4*, *5*). What was missing then was the episodic repetitiveness that has characterized subsequent activity, providing the opportunity to recognize precursory patterns and to develop hypotheses about the causes of the patterns.

We do not discuss forecasts further in this article, but we emphasize their importance in assessing a volcano's future, aiding long-range planning and land use, and reducing risk. In theory, forecasts may become increasingly specific and finally evolve into predictions. Whether some statements are termed predictions or forecasts may be arbitrary; then the volcanologist should assess the impact of each term on the intended audience before deciding which to use.

Techniques used for making predictions at Mount St. Helens. We describe here only those techniques that we have found most useful in making predictions. The single most important source of data for short-term predictions is seismic monitoring (*5*). Data are telemetered from 13 seismometers within 20 km of the volcano, one of which is usually located within the crater. We classify the seismograms into three major types: (i) deep earthquakes and those located away from the volcano, which produce high-frequency vibrations with impulsive first arrivals similar to those for tectonic earthquakes; (ii) shallow earthquakes, located under the dome at depths less than 3 km, which produce medium- to low-frequency vibrations; and (iii) surface events, such as rockfalls and energetic gas bursts from the dome, which produce complicated signatures with no clear beginning or end. Shallow volcanic earthquakes were observed in increasing numbers several days to from 1 to 2 weeks before each dome-building erup-

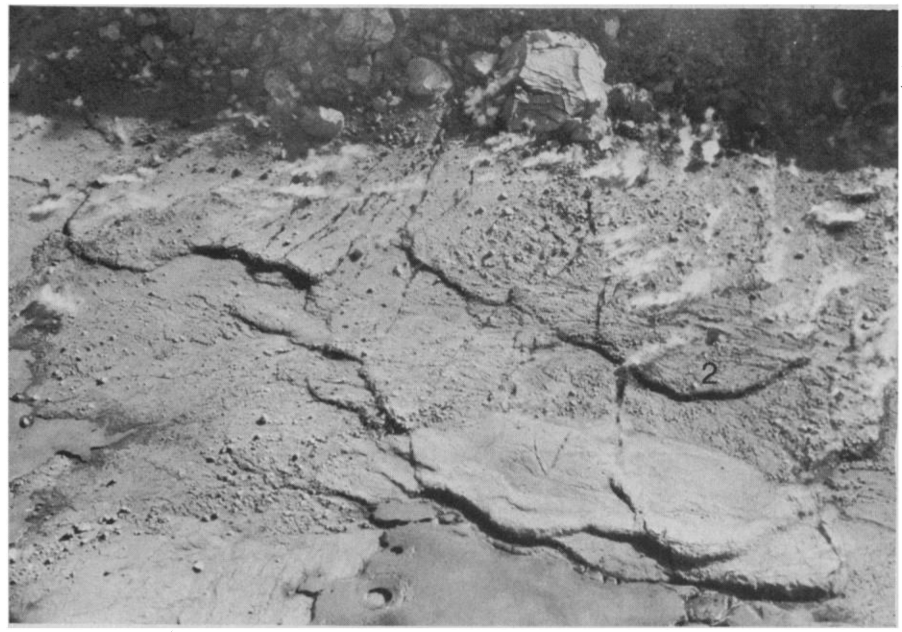


Fig. 2. Southwest part of the crater floor in June 1981, showing thrust faults, bounding tear faults, and radial cracks. The width of the view is about 200 m. Scarps define toes of the upper plates of thrust faults and are mostly directed away from dome, located off the top of the photo. Site 2 is on the upper plate of Christina 2 thrust (site 1 in Figs. 1 and 3).

tion in 1980 through 1982 (*5, 6*). Cumulative seismic-energy release (strain release) is calculated and plotted frequently as a preeruption sequence develops. The observation of a sudden pronounced upward turn in this smoothly increasing curve a few hours before the eruption begins [figure 2 in (*5*)] is the prime basis for our relatively short-term prediction. Once the eruption is under way, shallow volcanic events cease and surface events dominate. The seismic data, such as the times of degassing events on the dome, the occurrence of unobserved rockfalls associated with dome growth, and the depths of earthquake sources within the magma-conduit system, are also crucial for nonpredictive purposes. The seismic data are also used in a nonpredictive manner for determining such things as the times of degassing events and unobserved rockfalls on the dome and the depths of earthquake sources within the magma-conduit system.

Records of changes in the inclination of the ground surface have been particularly useful for short-term predictions. Electronic tiltmeters installed on the crater floor within tens to several hundred meters of the dome detect changes several weeks before an eruption (*7*). The rate of change begins to accelerate rapidly hours to several days before the eruption. The direction of tilting is generally outward from the dome, but this pattern is sometimes complicated by nearby cracks or faults. Often the tiltmeters record a reversal of tilt direction (usually inward) minutes or hours before the eruption. Tiltmeter data are commonly cross-checked by repeated leveling surveys.

Tilt measurements are one element of the single most reliable means of predicting eruptions several days to 2 to 4 weeks in advance—monitoring deformation of the crater floor and dome. Geodetic monitoring of Mount St. Helens, begun in April 1980, was resumed soon after the 18 May 1980 eruption with the reestablishment of a network on the outer flanks of the volcano (*8*). Small changes in the shape of the volcano were detected before the eruptions of July, August, and October 1980. Changes were particularly notable at points within the crater as measured from Harry's Ridge, 8.5 km north of the vent. This observation spurred us to focus on the crater during the fall and winter of 1980 and 1981. Initial results of monitoring within the crater led to informal, nonpublicized "predictions" of the December 1980 and February 1981 eruptions several days in advance. Since then, we have issued relatively long-term public predictions before eruptions. These predictions have been based largely on measurements of deformation in the crater (Table 1).

New cracks radial to the center of the dome appear on the crater floor several days to 2 to 4 weeks before an eruption [figure 1 in (*9*)]. Distance measurements across cracks made with a steel tape often show continual widening or strike-slip movement that accelerates before eruptions.

Parts of the crater floor often become slightly wrinkled several weeks before an eruption. The wrinkles apparently form because the floor is being shoved against the relatively rigid crater walls. A few of the wrinkles develop into thrust faults roughly tangential to the dome (Fig. 2). The upper plate of most of the thrusts moves upward and outward from the dome. We monitor movement by repeated taping and leveling between points on the upper and lower plates. Before eruptions, the horizontal distances between these points decrease and the vertical separations increase, both at accelerating rates.

Measurements of cracks and thrust faults have provided the best basis for long-term predictions. They present the most consistent patterns, can be made during periods of poor weather and visibility (provided that access to the crater is possible), require only simple equipment (a steel tape), and can be conducted by as few as two persons. Deep winter snow presents the most difficult problem.

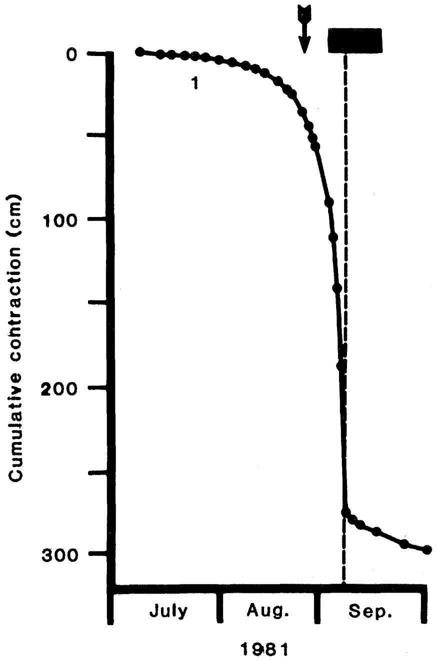


Fig. 3. Cumulative contraction of taped distance across the toe of Christina 2 thrust fault plotted against time before the September 1981 eruption. The arrow indicates the date on which relatively long-term prediction was issued. The black rectangle is the period within which the eruption was predicted to occur (predictive window). The dashed line designates the date of the start of the eruption. The location of the thrust fault is shown in Figs. 1 and 2.

Measurements of the slope distance and vertical angle between points on the crater floor and the dome, made with a laser distance meter and theodolite, document preeruption "endogenous growth," a process in which the dome swells from the injection of magma (*9*). Swelling begins 3 to 4 weeks before extrusion and accelerates as the eruption nears. We measure routinely from four to five stations on the crater floor to 10 to 20 targets on the dome; that coverage made possible accurate, relatively long-term predictions of all the eruptions in 1982. Disadvantages of this method include the potential for malfunction of the relatively sophisticated equipment and the need for good visibility, which is often limited by fog and fume.

Using airborne techniques, we monitor the emission rates of SO_2 and CO_2 in the plume above the volcano. Changes in these rates were useful in anticipating eruptions in August 1980 (when CO_2 decreased) (*10*) and June 1981 (when SO_2 increased) (*11*). However, CO_2 concentrations have been too low to measure since early 1981, and the SO_2 pattern of June 1981 has not been repeated. A gradual decrease in the emission rate of SO_2 since the summer of 1980 suggests a declining likelihood for strong explosions and is important in guiding forecasts of possible activity months in advance (*11*).

Examples of predictions. Three examples of the current prediction procedure at Mount St. Helens illustrate both relatively long- and short-term predictions and suggest ways in which each prediction could have been improved. The short-term predictions of explosive eruptions in June through October 1980 are discussed by Malone *et al.* (*6*).

Let us consider first the eruption of September 1981 [Fig. 3; figure 2 in (*5*)]. By 26 August, deformation of the crater floor had accelerated to rates comparable with those observed 1 to 3 weeks before earlier dome-building eruptions. Thus a relatively long-term prediction (*12*) was issued stating that a nonexplosive, dome-building eruption was likely within a 2-week period starting 1 week after 26 August.

An increased number of shallow earthquakes concurrent with a further increase in the rates of crater-floor deformation prompted a relatively short-term prediction at 0800 P.D.T. on 6 September: "Based on previous preeruption patterns, a dome-building eruption accompanied by increased fume but little or no ash emission will probably begin within the next 12 to 48 hours." Seismicity, rate of tilt, and the frequency and size of rockfalls from the visibly disrupted northeast flank of the dome all peaked at midday, leading to a revised prediction at 1330 P.D.T.: "Seismicity and crater tilt have increased significantly within the past 4 hours, and the expected eruption will probably begin within the next 12 hours." Slow extrusion of lava on the northeast flank of the dome probably began in midafternoon, although definite evidence of it was not recognized until 1800 P.D.T.

This set of long- and short-term predictions was adequate but could have been better. By 3 September, the crater floor was deforming so rapidly that the long-term prediction could have been revised to state the likelihood of an eruption within 5 days. This would have provided a good transition between the 2-week and 12- to 48-hour predictions. Such updating has been done for several subsequent eruptions (Table 1).

Now let us examine the eruption of March to April 1982 [Fig. 4; figure 2 in (*5*)]. At 0900 P.S.T. on 5 March, the following nonpredictive statement was publicly released:

> Seismicity at Mount St. Helens increased around 21 February and has remained at a level somewhat above background since that time. Approximately 100 earthquakes . . . fall into two groups: (i) a "deep" group of very small earthquakes with centers at 6 to 11 km depths, and (ii) a shallow group of somewhat larger (magnitude 1 or less) earthquakes located at 3 to 4 km up to the surface. . . . Measurements made last week [on 27 February] show only slow ground deformation . . . and no significant increase in gas emissions. . . .

Measurements made later on 5 March showed that deformation of the north flank of the dome and adjacent crater floor had accelerated markedly. Two thrust faults on the west side were also moving faster; deep snow prevented measurements elsewhere in the crater.

At 0800 P.S.T. on 12 March, a relatively long-term prediction was issued:

> Seismicity beneath Mount St. Helens continues at elevated levels, but individual earthquakes are of low magnitude. . . . Rates of ground deformation in the crater area have increased during the last 2 weeks. . . . Based on rates of deformation, an eruption is likely within the next 3 weeks. Deformation is confined to the crater area, suggesting that renewed dome growth will occur. The current seismic patterns differ from any observed before 1980 and 1981 eruptions, however, and raise the possibility of more hazardous variations in eruptive behavior. If there were to be any pyroclastic flows . . . , the possibility of rapid snowmelt would be a concern.

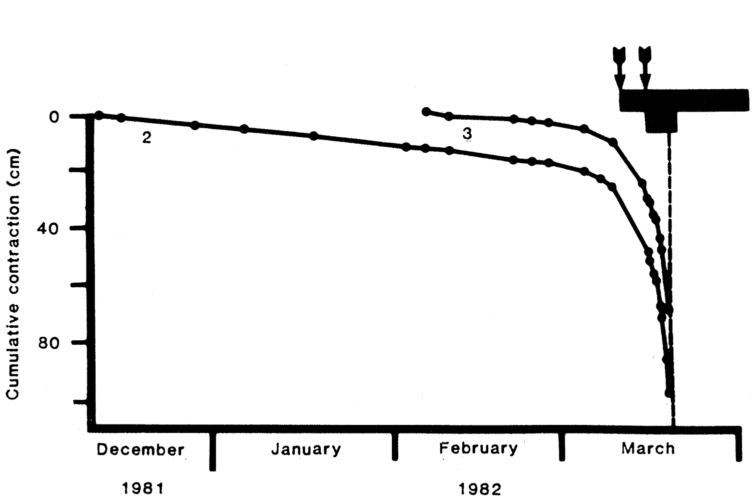
The mention of possible hazardous behavior triggered a deluge of media interest, both local and national, and some greatly exaggerated television and newspaper accounts. The long eruption window in the statement was intentionally conservative, because we had fewer data than before most earlier eruptions.

Measurements on 15 March showed greatly accelerated deformation, and so the prediction was updated at 1900 P.S.T.: "An eruption, most likely of the dome-building type, will probably begin within 1 to 5 days." This prediction made no further mention of explosive potential (although we always emphasized this hazard in interviews), because of the overblown media response to the initial statement.

Rates of deformation and seismic energy release continued to increase rapidly. At 0900 P.S.T. on 19 March, a relatively short-term prediction based on increased seismicity during the past day stated that "an eruption would begin soon, probably within 24 hours. The character of both the seismicity and deformation in the crater area indicate that the most likely type of activity is dome growth."

The eruption began at 1927 P.S.T. on 19 March, preceded by about 2 hours of intense seismicity stronger than any since 1980. The first stage of eruption was a southward-directed explosion that hurled blocks of hot pumice against and over the south wall of the crater and generated a large avalanche within the crater. Rapid melting of snow produced a flood that eventually reached the Toutle River Valley (*13*). Soon after the explosion, a tephra-laden eruption cloud reached a height of 14 km. Extrusion of new lava on the southeast flank of the dome began about a day later and accounted for most of the volume of erupted material.

For this part of the eruption, the predictions of the time and dominance of the dome-building stage were satisfactory. Whether the possibility of explosive behavior had been stressed sufficiently is open to question. We believed that it was, but most of the news reporters



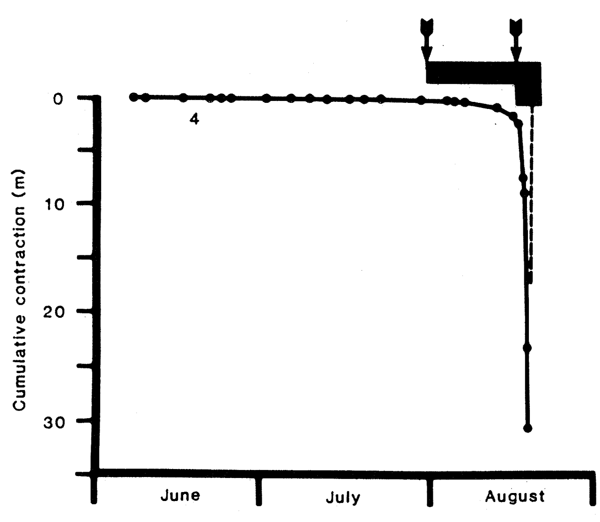


Fig. 4 (left). Cumulative contraction of slope distances 2 and 3 (Fig. 1) plotted against time before the eruption of March and April 1982. Symbols are as in Fig. 3. An updated, relatively long-term prediction with a shorter predictive window was issued 3 days after the initial prediction. Fig. 5 (right). Cumulative contraction of slope distance 4 (Fig. 1) plotted against time before the August 1982 eruption. Note the change in the ordinate scale as compared with Figs. 3 and 4. Symbols are as in Fig. 3. An updated prediction with a short predictive window followed the initial prediction.

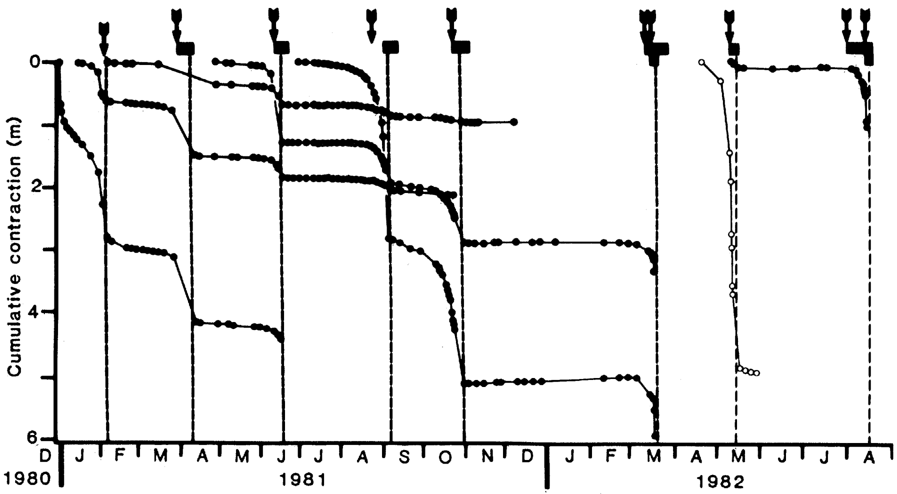


Fig. 6. Diagram summarizing the displacement data for selected thrust faults (closed circles) and one target on the west flank of the dome (open circles), dates on which relatively long-term predictions were issued (arrows), predictive window, and dates of the start of eruptions, late December 1980 through August 1982. Symbols are as in Fig. 3.

disagreed. Their reaction surprised us, in view of the nationwide attention that the 12 March prediction had received. We learned from this that an important statement, once made, should be repeated with each revised prediction unless there is strong reason not to do so.

The new lobe continued to grow until about 22 to 24 March; the exact time of cessation is impossible to determine. A statement released at 1730 P.S.T. on 24 March stressed: "Rates of deformation on the north side of the dome have increased [over the past 2 days]. . . . Until additional measurements are made, it would be premature to declare this eruption over. . . ." Measurements the next day confirmed the increasing rates.

Bad weather prevented access to the crater until 4 April, when new rockfalls from the north side of the dome were seen and interpreted as evidence of continued swelling of the dome. These falls, accompanied by increased seismicity, intensified in late afternoon, and appropriate individuals were notified (*12*). At 2052 P.S.T. a plume containing a minor amount of tephra was ejected; a second weak plume was witnessed at 0035 P.S.T. on 5 April. On the morning of 6 April, we observed a new lobe high on the north flank of the dome. By 12 April, seismicity, deformation, and gas emission had returned to low levels, and the eruption was declared over.

Whether the March and April events should be considered as one or two eruptions is largely a question of terminology. The last measurements before the April event showed increased rates of deformation while extrusion continued, and so we stated publicly that the eruption was not over. We stood by this statement until the April event, because we had no data to contravene it. In fact, airborne gas measurements remained high throughout the interval. We believe it is important not to modify a public statement until evidence dictates a change.

The last example of eruption prediction that we wish to discuss occurred in August 1982 [Fig. 5; figure 2 in (*5*)]. A relatively long-term prediction released on 30 July stated:

> Seismicity and rates of deformation of the dome and crater floor have increased over the past week. . . . If current trends continue, an eruption will probably begin within the next 3 weeks. . . . The eruption will [probably] consist primarily of dome growth, but, as with all dome growth, minor explosive activity is also possible.

This prediction was based largely on increased seismicity; rates of deformation were not showing well-defined trends. Measurements of deformation the next day detected slower rates, and seismicity soon dropped nearly to background level. We discussed changing the prediction, but the lesson of March and April 1982—to stick by a public statement until the data force a change—had been learned. Within a few days, the rates of deformation began to increase systematically and it became clear that an eruption was coming, although possibly later than had been predicted.

By mid-August, movement of the west side of the dome and the west crater floor was accelerating rapidly. Increased seismicity and deformation prompted an updated prediction at 1130 P.D.T. on 16 August that a dome-building eruption, possibly with "minor explosive activity," would "begin within the next 4 days, possibly within the next 2 days."

At 0655 P.D.T. on 17 August, a statement based on seismicity and deformation predicted the onset of eruption within the next 24 hours. No extrusion or explosion had occurred by next morning, however. Instead, the dome was swelling at a rate of 3 m per hour, and endogenous growth was in its final stage. An updated prediction released at 0745 P.D.T. on 18 August explained that rapid endogenous growth could be considered as the early stage of eruption. By 1000 P.D.T., extrusion had begun high on the west side of the dome. Thus the eruption took place within the 3-week time interval predicted on 30 July, although just barely.

We learned two lessons from this eruption. One is that the most coherent data, and those that can be interpreted on the basis of experience, should form the prime basis for prediction. The relatively long-term prediction was based mainly on increased seismicity, not accelerating deformation. Up to then, deformation had been the most definitive clue for long-term prediction, and it was not showing a clear trend when the prediction was made. In retrospect, we believe that we should have publicly noted the significant increase in seismicity but refrained from predicting an eruption until about a week later, when deformation was accelerating and all data were internally consistent.

The second lesson is that the exact onset time of some eruptions can be difficult to define. The prolonged period of endogenous growth in mid-August 1982 gave us a chance to make that point publicly.

Predicting record, 1980 through 1982. Our record for predicting eruptions at Mount St. Helens to the end of 1982 is summarized in Table 1, Fig. 6, and figure 2 of (*5*). All 13 eruptions starting with the one on 12 June 1980 have been predicted tens of minutes to, more generally, a few hours beforehand, chiefly on the basis of seismicity. All seven eruptions starting with that of mid-April 1981 have been predicted between 3 days and 3 weeks beforehand, chiefly on the basis of deformation; the 3-day period was so short because poor weather interfered with the acquisition of necessary data. Equally important, we have issued no incorrect predictions ["false alarms" (*14*)]. This record has resulted in a high degree of confidence in our predictions by governmental officials, industry, and the public.

Predictions now are largely heeded, and decisions concerning land use and restrictions on access are based substantially on them (*15*).

We believe that future eruptions can be predicted, provided that the style of repeated, short-lived dome-building events continues, funding remains adequate, and prolonged bad weather neither prevents access to the crater nor causes loss of telemetry. Should the style of activity change, for example, to a more explosive mode or to more nearly continuous effusion, we would probably recognize changes in precursory patterns but might not know what the outcome would be. If the changed activity itself becomes repetitive, then modifications of existing techniques might enable us to continue to make predictions. In any case, experience is crucial. We must be able to observe repeated episodes if we are to acquire knowledge of causes and to gain confidence in our predictions. Only rarely will an initial episode have such an obvious cause that the course of coming events can be correctly predicted.

Remaining problems. Our Mount St. Helens prediction system needs at least two kinds of improvement: (i) we need to be able to discriminate between predominantly explosive and predominantly nonexplosive eruptions, and (ii) we need to be able to anticipate the duration and end of an eruption.

Geodetic data suggest that the entire volcano expanded before explosive eruptions in the summer and fall of 1980 (*8*). Such expansion has not been noted subsequently, during a period of predominantly nonexplosive behavior. In considering this seeming distinction between explosive and nonexplosive precursors, one should keep two caveats in mind: (i) the data for 1980 are not conclusive, for some of the measured changes are barely above expectable surveying error, and (ii) no predominantly explosive eruption has occurred since 1980 to test whether the edifice would again expand beforehand or whether the response of the volcano has changed with time. Differences between the precursory seismic patterns before the 1980 explosive eruptions and those preceding later nonexplosive eruptions are small and not understood in terms of differences between the eruption mechanisms. One or more new episodes of significant explosive activity would help us to evaluate possible differences in precursors and to test hypotheses.

Extended periods of land closures during eruptions would be minimized if we could predict the end of an eruption, the time at which new lava or tephra stops reaching the surface. As yet, we cannot identify that moment precisely. New lobes continue to move at gradually decelerating rates for many days after extrusion ends, owing to the creep of already erupted viscous lava down the steep dome. Seismicity also declines slowly, with no obvious break to mark the end of extrusion. The SO_2 emissions increase sharply at the start of extrusion and then decrease gradually, returning to the background level within several days. The end of the eruption occurs sometime during this long period of decaying movement, seismicity, and gas discharge.

Application to other volcanoes. We believe that the predictive methods used at Mount St. Helens can be applied to other volcanoes that erupt lava of predominantly andesitic and dacitic composition, provided that adequate funding and trained personnel are available. Seismic surveillance has long been used for monitoring volcanoes (*16*). Deformation and gas monitoring have not been as widely applied (*17*). We recommend that any surveillance program should include monitoring of deformation and gas emissions, in addition to the use of a seismic network with telemetry capability. We recommend stratigraphic studies also, because knowledge of the geologic history of a volcano provides an important context within which to interpret the results of monitoring.

Telemetered data are best interpreted in a system of frequent field observations and measurements near the vent; periodic field measurements are best understood in the context of the continuous records and up-to-date information provided by telemetry systems. Neither style of monitoring stands securely on its own. The accuracy of our predictions depends on interactive use of all data by cooperating geophysicists, geologists, and geochemists. Such teamwork should greatly enhance any program of eruption prediction.

Predictions are rarely possible when an andesitic or dacitic volcano resumes activity after a long period of quiescence (*18*). If adequate seismic and deformation monitoring has been maintained, however, changes before such activity will probably allow forecasts. Where practical considerations limit the monitoring to that of an "adequate minimum observatory" (*19*), the operations of such a monitoring group could include contingency plans to permit swift expansion into a system of the Cascades Volcano Observatory type as soon as an eruption is forecast. Then, if the renewed activity becomes episodic, the time and type of eruptions may be made predictable if the types of monitoring techniques used at Mount St. Helens are initiated.

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12. Predictions and related information are provided in writing to the U.S. Forest Service and the Washington Department of Emergency Services. These agencies relay the message by telephone to NAWAS (National Warning System), federal agencies (Federal Aviation Administration, National Weather Service, U.S. Air Force, U.S. Coast Guard, U.S. Army, National Aeronautics and Space Administration, Federal Emergency Management Agency, National Resources Committee, Army Corps of Engineers, and Bureau of Indian Affairs), state agencies (State Patrol, National Guard, Natural Resources, Transportation, Health, Agriculture, and others), all counties in Washington and Oregon, public utilities, the timber industry, and the news media. The U.S. Geological Survey also notifies the Smithsonian Institution's Scientific Event Alert Network and, upon request, researchers in volcanology, atmospheric sciences, ecology, health sciences, and other disciplines. All concerned parties are notified, around the clock, within 30 minutes from the time we issue a prediction.
13. R. B. Waitt, Jr., T. C. Pierson, N. S. MacLeod, R. J. Janda, Barry Voight, R. T. Holcomb, *Science* **221**, 1394 (1983).
14. R. W. Decker [*U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 815] stated that eight "false alarms" occurred in 1980. Each false alarm alerted the scientists, not the public, and was based on a minor event at the volcano that could not be confirmed by other data. No public action was taken on the basis of the alarms, for it was recognized that more data were needed.

15. Recognition by public authorities of the current prediction capability has permitted lumbering operations to continue close to the volcano and has resulted in significant reduction of the restricted zone. Most of the new National Volcanic Monument is now open to the public, as the result of a policy decision that would have been unlikely in the absence of good predictive capability. Revenue from the increased logging and recreation has been substantial.
16. D. Shimozuru, in *The Surveillance and Prediction of Volcanic Activity* (Unesco, Paris, 1972), p. 19.
17. R. W. Decker and W. T. Kinoshita, *ibid.*, p. 47; F. Tonani, *ibid.*, p. 145.
18. A notable exception was the 1976 eruption of Ploskii Tolbachik volcano, Kamchatka, correctly predicted by P. I. Tokarev [*Bull. Volcanol.* **41** (No. 3), 251 (1978)] on the basis of seismicity after 34 years of quiescence. The products of that eruption, however, were basaltic, not intermediate and silicic as at Mount St. Helens. The public prediction specified the time period (2 days) and the location (a new vent 17.5 km from the central crater). A forecast made in 1970 had given a probability of 0.7 for an eruption between 1964 and 1978.
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20. Responsibilities within the Mount St. Helens Monitoring Program are as follows: D.A.S., most deformation studies and crater observations; T.J.C., gas emission; D.D., tilt and crater geophysics; S.D.M. and C.S.W., seismicity; and C.G.N., forecasting and hazard assessment. We thank R. W. Decker, R. T. Holcomb, N. S. MacLeod, D. W. Peterson, R. B. Waitt, Jr., and R. E. Wallace for helpful reviews. We are indebted to the support staff of the Cascades Volcano Observatory (D. W. Peterson, scientist-in-charge) and of the Geophysics Program of the University of Washington, without whom the prediction system would still be floundering.

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Seismic Precursors to the Mount St. Helens Eruptions in 1981 and 1982

Abstract. *Six categories of seismic events are recognized on the seismograms from stations in the vicinity of Mount St. Helens. Two types of high-frequency earthquakes occur near the volcano and under the volcano at depths of more than 4 kilometers. Medium- and low-frequency earthquakes occur at shallow depths (less than 3 kilometers) within the volcano and increase in number and size before eruptions. Temporal changes in the energy release of the low-frequency earthquakes have been used in predicting all the eruptions since October 1980. During and after eruptions, two types of low-frequency emergent surface events occur, including rockfalls and steam or gas bursts from the lava dome.*

A wide variety of seismic signals are generated at volcanoes (*1*). Rapid increases in the number and energy of volcanic earthquakes have been used to predict eruptions at several volcanoes (*2*). The cataclysmic eruption of Mount St. Helens on 18 May 1980 was preceded by 2 months of very intense volcanic seismicity. Although no specific prediction was made for this eruption, subsequent explosive eruptions in the summer and fall of 1980 were predicted hours before they occurred by the observation of increasing rates of seismic events (*3*).

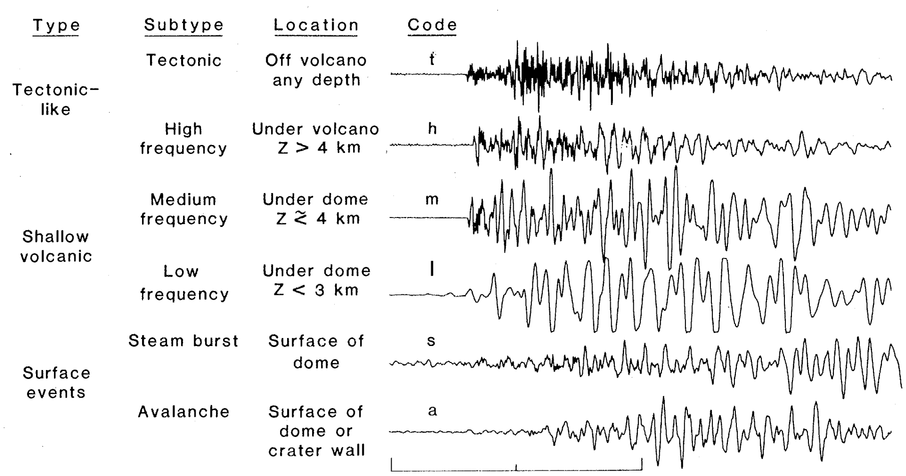

Fig. 1. Characteristic seismograms for the six categories of events observed at Mount St. Helens. Seismograms are from station SHW, located 3.6 km west of the active dome. The example of type t is from a tectonic earthquake located 8.2 km south of the dome at a depth of 5.6 km; type h, a high-frequency volcanic earthquake located under the dome at a depth of 6.2 km. The remaining four events occurred at shallow depth or at the surface near the dome: the example of type m is from a medium-frequency volcanic earthquake; type l, a low-frequency volcanic earthquake; type s, an observed gas burst from the top of the dome; type a, a rock avalanche from the south crater wall.

Between the explosive eruptions of 16 to 18 October 1980 and the end of 1982 there were ten relatively nonexplosive dome-building eruptions, each of which added several million cubic meters of new lava to a composite dome. Each of these eruptions was preceded by recognizable seismic precursors, which were used to anticipate the time of the volcanic eruptions. We describe here the precursory seismic events and the time sequence of their energy release as it was used to predict the eruptions.

As part of our daily monitoring effort at Mount St. Helens, we review the seismograms from several local stations. We have found it useful to classify the seismic events into three broad categories: (i) tectonic-like earthquakes with focal depths greater than 4 km or epicenters away from the volcano, which produce high-frequency, impulsive arrivals; (ii) earthquakes with focal depths of less than 3 km under the crater which produce medium- to low-frequency arrivals; and (iii) seismic events that are associated with surface or near-surface phenomena, such as rock avalanches and vigorous gas bursts from the dome, which produce very emergent, poorly defined arrivals. We have subdivided each of these categories into two groups, on the basis of the characteristics of the seismograms, the location of the event, observable surface phenomena, or some combination of these. Figure 1 shows characteristic seismograms for the six types of events. One can usually assign an event to one of the three major categories by using seismograms from several key stations. The assignment of events into subcategories, however, is often ambiguous.

The tectonic-like events have been divided into those whose foci are directly under the mountain (type h) and those whose epicenters lie at a significant distance away from the mountain and whose occurrences are unrelated to volcanic activity (type t). The type-t events can usually be distinguished from the type-h events on the basis of their location if the seismograms are not diagnostic enough. The shallow volcanic events have been divided, somewhat arbitrarily, into those with impulsive, fairly well-defined arrivals of medium-frequency content (type m), and those with emergent, nondistinct arrivals of very low-frequency content (type l). The type-m events contain peak frequencies in the range 1.0 to 5.0 Hz, whereas the frequency content of type-l events is 0.5 to 2.0 Hz. Because these two types grade into one another, the distinction between them is left to the analyst's discretion.