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.
19. G. E. Sigvaldason, *Volcano News* **8**, 6 (1981); R. I. Tilling, *Earthquake Inform. Bull.* **14**, 185 (1982).
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.

26 January 1983; revised 15 June 1983

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*).

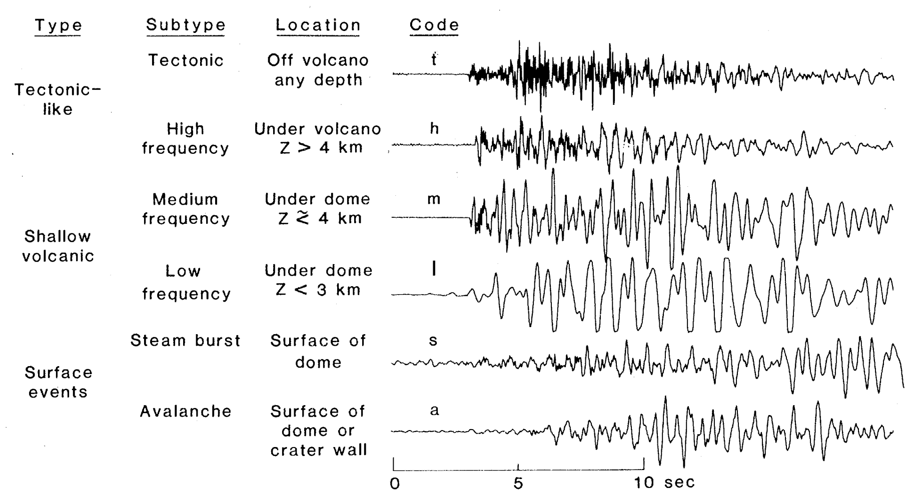

Fig. 1. Characteristic seismograms for the six categories of events observed at Mount St. Helens. Seismograms are from station SHW, located 3.6 km west of the active dome. The example of type t is from a tectonic earthquake located 8.2 km south of the dome at a depth of 5.6 km; type h, a high-frequency 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.

The surface-source events (type s and type a) have a variety of seismic waveforms. They are usually characterized by very emergent first arrivals, low maximum amplitudes compared with their durations, no distinct phases, and a fairly broad spectrum between 0.5 and 5 Hz. The steam or gas burst events (type s) often display a high-amplitude set of arrivals buried in the middle of lower amplitude signals. The avalanche signals (type a) typically begin slowly, build to a maximum over tens of seconds, and then decay gradually.

Over the past 2 years, we have learned to recognize certain characteristic patterns of seismic activity that precede and accompany eruptions. The rate of activity of the various categories of events is used to predict the volcanic activity at the mountain. By plotting the energy release of the different classifications of events versus time (Fig. 2), we have developed a qualitative model for the seismic activity associated with the eruptive process. Because the high-frequency events (type h and type t) have no obvious direct relation with the timing of eruptions, data from these events are not used as predictive tools.

A rigorous quantitative determination of the energy release for the various events at Mount St. Helens requires knowledge of the mechanisms of the events. In lieu of such knowledge, we assume that local magnitude, as determined by coda-duration, may be used to estimate the energy release of the earthquakes (*4*). The coda-duration magnitude scale was derived empirically, using magnitudes determined from standardized Wood-Anderson seismographs (*5*). Energy estimates of surface events are less reliable. The mechanism of seismic-energy generation for these events is certainly much different from that for earthquakes. The surface events have multiple sources which operate over many seconds or even tens of seconds. For these events, maximum trace amplitude and duration are used to match its seismic energy to that of a volcanic earthquake of known magnitude recorded at the same station. These procedures for determining energy release are far from ideal, but they can be easily and quickly applied to the visual paper records of the events. The energy-release estimates may be in error by as much as an order of magnitude, but they are still useful for the comparisons shown in Fig. 2.

At Mount St. Helens, significant seismic energy release is concentrated around the time of the eruptions. A typical dome-building eruption episode begins with the occurrence of a few type-m events several weeks before the eruption. It is difficult to recognize the precise start of the precursory seismicity, for there is always some residual seismic activity. Plots of the cumulative square root of energy released [$\Sigma(E_s)^{1/2}$] (Fig. 2) are updated frequently to detect increases in activity. Once a significant increase is recognized and after consultation with scientists observing gas emissions and deformation rates in the crater, an advisory is issued indicating that an eruption is likely within a stated number of weeks or perhaps days. As the energy-release level increases, there is a gradual transition from type-m to type-l events that is particularly noticeable in the hours just prior to the eruption. Also, before most eruptions, there is an abrupt increase in the cumulative energy-release curve. These two diagnostic changes prompt the release of a warning alert, stating that the eruption is likely to begin within 24 hours. When the extrusion actually starts, the type-m and type-l events are replaced by type-a and type-s events; the cumulative energy-release curve for earthquakes flattens while that for surface events steepens. Usually type-a events dominate during the first few hours, and then type-s events follow. Events of both types may last for several days, slowly decreasing in number and size.

The increase in seismic activity before eruptions most likely reflects increasing stress in the country rock generated by magma as it approaches the surface. For

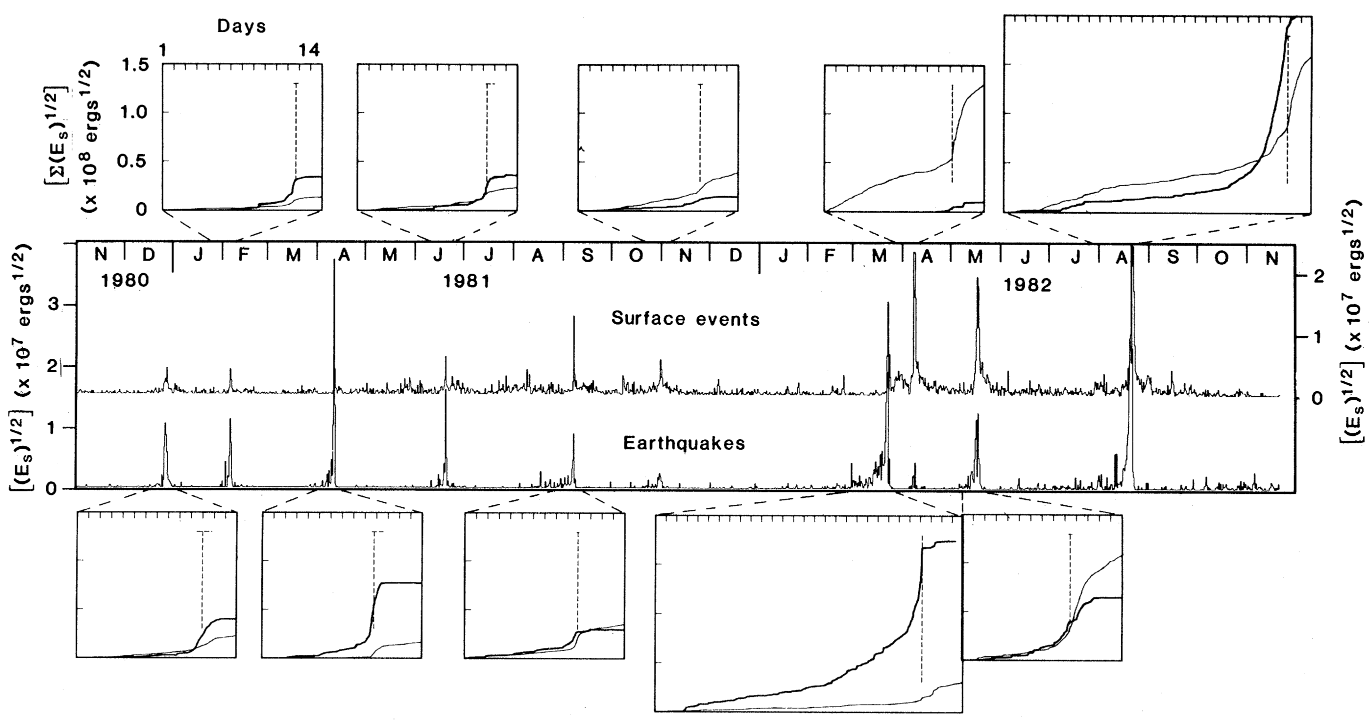

Fig. 2. The square root of seismic energy release [$(E_s)^{1/2}$] per half day from 1 November 1980 to 20 November 1982. Surface events (types s and a) are plotted separately from earthquakes (types m and l). The cumulative $(E_s)^{1/2}$ released during a 2-week period (a 4-week period in the case of the March 1982 and August 1982 eruptions) around each of the eruptions is shown near the time of each eruption. Light lines represent surface events, and heavy lines represent shallow earthquakes. Each vertical dashed line indicates the most likely time of the beginning of an eruption.

many of the 1981 eruptions at Mount St. Helens, no unusual change in the seismic pattern was evident until after ground deformation near the dome had been reported (*6*). This absence of seismic events implies that strain rates were not high enough at that time to cause earthquakes; under those conditions the rock around the rising magma could deform plastically. As the magma neared the surface, either the strain rate increased, causing the rock to fracture, or the near-surface rock was cool enough so that even at the same strain rate it could not deform without brittle failure. We speculate that the change from type-m to type-l events represents a transition of the maximum deformation front from one rock type to another. The type-m events are, on the average, slightly deeper (1 to 3 km below the dome) than the type-l (0 to 2 km) events. Alternatively, the difference in waveforms may reflect different source mechanisms, such as shear versus tensile failure or gas explosions within the magma. The direction of first motion for most events is not clear, and so reliable focal mechanisms cannot be determined. The change from low-frequency shallow earthquakes (types m and l) to surface events (types s and a) apparently coincides with the beginning of the extrusion. Once the magma reaches the surface, the strain rate drops and no new rock is fractured.

This pattern, with minor variations, has been common to all ten eruptions. In particular, the eruption of 19 March 1982 was preceded by an anomalously long period of precursory seismicity that included both the typical shallow (types m and l) events as well as a swarm of very small, deep, type-h events (*7*). The eruption on 4 April 1982 was preceded by only a very brief, small increase in both type-l and type-s events. There appears to be a relation between the duration of the time period of precursory events to an eruption and the time interval since the previous eruption. The longer the interval between eruptions, the longer and stronger the precursory seismicity pattern. At one extreme is the 4½-month quiescence before the eruption of 19 March 1982, whose precursory seismic events lasted almost a month. At the other extreme is the inter-eruption period of 2 weeks preceding the eruption of 4 April 1982, all of whose precursory seismic events took place in less than a day. Between these two extremes lie most of the eruptions of 1981 and 1982, which occurred about every 2 months and which had seismic precursors lasting about a week.

If the eruptive process remains fundamentally unchanged, we believe that it will be possible to predict the timing of future eruptions of Mount St. Helens using techniques outlined here. The eruption of 19 March 1982 had a small explosive component that was not specifically anticipated. Consequently, we are not as confident of our ability to predict whether future eruptions will be explosive, with high-hazard potential, or nonexplosive, with relatively low hazards.

STEPHEN D. MALONE
CHRISTINA BOYKO
Geophysics Program, University of Washington, Seattle 98195
CRAIG S. WEAVER
U.S. Geological Survey at University of Washington

References and Notes

1. T. Minakami, in *Physical Volcanology*, vol. 6 of *Developments in Solid Earth Geophysics*, L. Civetta, P. Gasparini, G. Luongo, A. Rapolla, Eds. (Elsevier, Amsterdam, 1974), pp. 1–28; J. H. Latter, *Volcanological Observation at Tongariro National Park* (Publication No. 150, Department of Scientific and Industrial Research, Taupo, New Zealand, 1979).
2. P. I. Tokarev, *Bull. Volcanol.* **35**, 243 (1971); D. Shimozuru, in *The Surveillance and Prediction of Volcanic Activity* (Unesco, Paris, 1972), pp. 19–45.
3. S. D. Malone, E. T. Endo, C. S. Weaver, J. W. Ramey, *U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 803.
4. C. Richter, *Elementary Seismology* (Freeman, San Francisco, 1958), pp. 365–366.
5. E. T. Endo, S. D. Malone, L. L. Noson, C. S. Weaver, *U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 93.
6. D. A. Swanson *et al.*, *Science* **221**, 1369 (1983).
7. C. S. Weaver, J. E. Zollweg, S. D. Malone, *ibid.*, p. 1391.
8. This work was supported by U.S. Geological Survey contract 14-08-0001-19274.

26 January 1983; revised 28 June 1983

Deformation Monitoring at Mount St. Helens in 1981 and 1982

Abstract. *For several weeks before each eruption of Mount St. Helens in 1981 and 1982, viscous magma rising in the feeder conduit inflated the lava dome and shoved the crater floor laterally against the immobile crater walls, producing ground cracks and thrust faults. The rates of deformation accelerated before eruptions, and thus it was possible to predict eruptions 3 to 19 days in advance. Lack of deformation outside the crater showed that intrusion of magma during 1981 and 1982 was not voluminous.*

Ground deformation has been used to forecast volcanic eruptions at some volcanoes (*1*). Magma ascending beneath a volcano forcefully displaces the surrounding rock, and the resulting deformation can be measured at the surface. Such monitoring quantifies precursory patterns of deformation upon which eruption predictions can be based (*2*) and provides data on eruption processes. Deformation monitoring at Mount St. Helens has been used with unprecedented success in predicting the nine dome-building eruptions that occurred between December 1980 and the end of 1982 (*2*, *3*).

Five methods are used to measure deformation at Mount St. Helens: (i) trilateration and triangulation around the volcano to monitor the changes in the shape of the volcanic edifice; (ii) long-ranging distance measurements to points in the crater made from Harry's Ridge, 8.5 km north of the lava dome; (iii) measurements of short horizontal and vertical distances across active cracks and thrust faults on the crater floor; (iv) slope-distance and vertical-angle measurements from sites on the crater floor to targets on the floor and dome; and (v) measurements of ground tilts on the crater floor by means of electronic tiltmeters and precise leveling. The tilt studies are discussed by Dzurisin *et al.* (*4*); the other four methods are discussed below.

Before the eruption of 18 May 1980, a geodetic network on the outer flanks of Mount St. Helens was used to monitor the intrusion of magma that resulted in the growth of the famous "bulge" on the north flank (*5*). After 18 May 1980, the network was reestablished and expanded. Measurements during the summer and fall of 1980 suggested that the edifice expanded before eruptions and contracted afterward (*6*). However, since late 1980, measurements approximately once a month have shown no changes beyond expected survey error.

In the summer of 1980, we initiated slope-distance and vertical-angle measurements from Harry's Ridge to points inside the crater. Distances to points north of the vent shortened before eruptions (*6*). These measurements provided the first convincing evidence for ground deformation preceding eruptions after 18 May 1980.

The inner crater is filled with deposits of the explosive eruptions of 1980 that are unconsolidated at the surface and welded below about 3 m. In September 1980, ground cracks were first observed on the crater floor; these cracks extended radially outward from the dome. Some cracks widened at rates that increased before eruptions (*6*). In addition,