Eruption Prediction Aided by Electronic Tiltmeter Data at Mount St. Helens

Abstract. *Telemetry from electronic tiltmeters in the crater at Mount St. Helens contributed to accurate predictions of all six effusive eruptions from June 1981 to August 1982. Tilting of the crater floor began several weeks before each eruption, accelerated sharply for several days, and then abruptly changed direction a few minutes to days before extrusion began. Each episode of uplift was caused by the intrusion of magma into the lava dome from a shallow source, causing the dome to inflate and eventually rupture. Release of magma pressure and increased surface loading by magma added to the dome combined to cause subsidence just prior to extrusion.*

Volcanologists have recently made significant strides in predicting eruptions and in mitigating volcanic hazards (*1*, *2*). We describe here how inexpensive electronic tiltmeters were used in the successful prediction of six effusive eruptions at Mount St. Helens during 1981 and 1982. Frequent explosive eruptions during 1980 and an otherwise hostile environment in the crater at Mount St. Helens demonstrated the need for inexpensive, expendable instruments to monitor ground deformation there. To meet that need, a biaxial bubble tiltmeter that uses commercially available bubbles and modern low-power electronics was developed by Westphal (*3*). The rugged design and construction of these meters made it possible for them to operate effectively in the Mount St. Helens crater until they were buried or incinerated by rockfalls, transported by mudflows, or crushed by thick snowpack.

During the period from May 1981 to August 1982, nine tiltmeters (Fig. 1) installed in the crater at Mount St. Helens were used to monitor six extrusive eruptions that approximately tripled the volume of the composite dome. Soon after station IMR was installed on 29 May 1981, telemetry indicated tilting outward from the dome in response to uplift of the crater floor (*4*), which gradually accelerated through mid-June. A public statement on 12 June, based on ground deformation and gas emission measurements, predicted an eruption in 1 to 2 weeks. Uplift accelerated sharply from approximately 40 μrad/hour (*5*) to 140 μrad/hour on 18 June, then abruptly changed to subsidence at 1700 P.D.T. (7 hours earlier than G.M.T.). This abrupt change in the tilt pattern, together with an increase in seismicity beneath the dome, prompted a prediction at 1715 that an eruption would occur within 12 hours. Telemetered data suggested that the anticipated extrusive eruption began that night, but darkness and poor weather delayed visual confirmation until 1150 on 19 June.

Deformation of the crater floor resumed in early July and accelerated through August; on this basis, a statement predicting an eruption in 1 to 3 weeks was issued on August 26 (2). Three tiltmeters on the east crater floor reported accelerating uplift until 4 to 5 September, when tilting at two of the sites (stations IMR and EPH) changed to relative subsidence. On the basis of this change and increased seismicity beneath the dome, a statement issued at 0800 on 6 September predicted that another dome-building eruption was imminent; the anticipated eruption began approximately 9 hours later. Rapid uplift continued at station GUL until the tiltmeter there was damaged by a rockfall several hours before extrusion began.

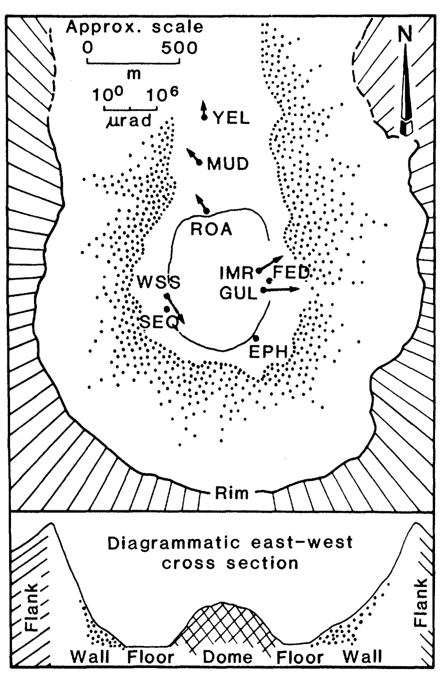

Fig. 1. Sketch map of the Mount St. Helens crater and composite lava dome showing the tiltmeter locations during May 1981 through November 1982. Net tilt vectors for periods that culminated in eruptions are shown on a logarithmic scale. Not all tiltmeters operated simultaneously; data are for the following intervals: station IMR, 29 May to 23 June 1981; station GUL, 3 July to 6 September 1981; stations YEL, MUD, and ROA, 13 October to 31 December 1981; station WSS, 29 April to 15 May 1982.

Eventually, stations IMR and EPH also were damaged by rockfalls; three new tiltmeters were then installed farther from the dome along a radial line to the north. Deformation of the crater floor adjacent to the dome (measured by other techniques) continued after the September eruption and accelerated through October. Tiltmeters at stations ROA, MUD, and YEL reported the beginning of uplift on 26 October, soon after a prediction was issued on 24 October that an eruption would occur within 2 weeks. Uplift accelerated at all three tiltmeter sites until the tilt pattern changed to relative subsidence on 30 October. At 1100 that morning, it was predicted that an eruption would occur within 24 hours; extrusion onto the northern flank of the dome was first observed early on 31 October.

Heavy snowfall, which began in November, hampered telemetry and prevented maintainence of stations MUD and YEL during the winter. Visits to station ROA revealed that uplift resumed there in mid-January 1982 and accelerated smoothly through early March (Fig. 2). On 12 March, an eruption was predicted to occur within 3 weeks; the prediction window was progressively narrowed to 1 to 5 days on 15 March and to 24 hours at 0900 on 19 March (*2*). Outward tilting at station ROA had reached 230 μrad/day when telemetry was reestablished on 16 March. This rate increased to 360 μrad/day before subsidence began abruptly at 1850 on 19 March. Telemetry was lost 30 minutes later, when the station was damaged by ejecta from the explosive onset of another eruption (*6*). Telemetry from station ROA was reestablished on 21 March, and by 2 April uplift had resumed. A public statement on 24 March cautioned that continuing deformation of the dome meant that the eruption might resume. Tilting accelerated rapidly until 1750 on 4 April, when uplift again changed to subsidence. About 2 hours later, station ROA was buried by a rock avalanche from the dome that signaled the onset of another episode of extrusion.

As soon as the tiltmeter at station WSS was installed on 27 April, it reported slow inward tilting which accelerated into early May. Leveling of a radial surveying line that included station WSS confirmed that the site was tilting inward, although parallel lines located less than 100 m to each side of the tiltmeter were tilting rapidly outward. Accelerated deformation was the basis for a 1-week eruption prediction issued on 11 May, which was updated to include a 36-hour prediction window at 2300 on 13

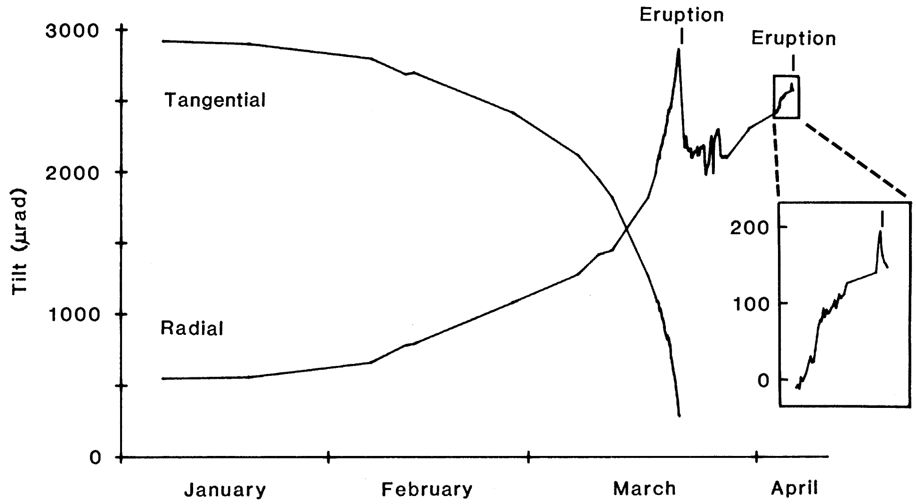

Fig. 2. Tiltmeter data from station ROA for the eruption of March to April 1982. Radial uplift began in mid-January and accelerated sharply on 16 March; rapid subsidence began 30 minutes before the explosive onset of the 19 March eruption. Uplift resumed in late March and then again reversed to subsidence 36 hours before extrusion resumed on 5 April (inset).

May. Inward tilting at station WSS continued to accelerate until it stopped abruptly just before midnight on 13 May. Observers reported incandescent rockfalls from the dome several hours later and confirmed the expected extrusion early the next morning.

On 8 July, a second tiltmeter (station SEQ) was installed about 70 m south of station WSS in an attempt to better define the zone of anomalous inward tilting. Soon thereafter, both instruments reported the onset of tilting which shifted progressively inward toward the dome and accelerated in mid-August. A 3-week eruption prediction issued on 30 July was based largely on a temporary increase in seismicity, but by 16 August all indicators pointed to an eruption in 2 to 4 days (*2*). Both tiltmeters recorded more than 2×10^3 μrad of inward tilt before going off-scale on 17 August, when the eruption window was narrowed to 24 hours. The predicted eruption began the next day, after a period of rapid dome growth. Both tiltmeters were retrieved before the sites were buried by rockfalls from the dome triggered by the new extrusion. Station FED was installed on 19 October; no significant deformation had occurred there by the end of 1982.

All seven extrusive episodes (March and April 1982 episodes are considered to be a single eruption) at Mount St. Helens during 1981 and 1982 were preceded by tilting of the crater floor, which accelerated progressively as the eruption neared. Sites within 50 m of the dome usually tilted by 10^3 to 10^4 μrad before each eruption, and in one case a site 500 m from the dome tilted by nearly 10^2 μrad. Before all but the August 1982 eruption, tiltmeters recorded an abrupt change in the pattern of tilt 0.5 to 48 hours before the eruption began. In five of six cases, the pattern changed from outward to inward tilt; prior to the May 1982 eruption, it changed from inward tilt to quiescence. Exceptions to the pattern of outward, then inward tilt (station GUL in September 1981, station WSS in May 1982, and stations WSS and SEQ in August 1982) can be accounted for in terms of intense deformation or faulting near the affected tiltmeters.

The repeated ascent of magma into the dome induces a complex but repetitive pattern of ground tilt on the adjacent crater floor. We interpret that pattern to be caused by prolonged uplift followed by rapid subsidence, except in areas of faulting or unusually rapid deformation. A similar pattern has been observed before eruptions elsewhere, including Kilauea and Mauna Loa volcanoes in Hawaii (*7*) and Krafla Volcano in Iceland (*8*).

Outward, then inward tilt is not a feature of elastic displacement models of magma intrusion, regardless of the shape used to model the magma body. For example, a dike intruding a homogeneous, two-dimensional half space causes uplift indented by a zone of relative subsidence immediately above the dike (*9*). Subsidence becomes increasingly localized as the dike approaches the surface, and some points that initially tilted inward may eventually tilt outward. However, existing models do not predict the opposite change from outward to inward tilt.

We therefore propose two other explanations for the observed tilt pattern at Mount St. Helens: magmatic pressure release and increased surface loading. In each mechanism, the crater floor is considered to be displaced upward initially by gradual intrusion from a shallow magma source (*10*). In the pressure release hypothesis, subsidence is triggered by rupture of the dome owing to inflation, which releases internal magma pressure and thereby allows the dome and floor to settle. According to the second hypothesis, the increased surficial load on the crater floor caused by magma accumulation in the dome might be responsible for settling before eruptions. The sudden onset of subsidence in most cases argues against this mechanism, which should cause a more gradual tilt change as upward intrusive forces are replaced by downward loading forces. Pressure release owing to rupture of the dome is thus the most likely cause of sudden rapid subsidence just prior to eruptions; increased surface loading may contribute to slowly waning subsidence after extrusion begins.

Every volcano presents a unique challenge to those faced with predicting eruptions, but experience at Mount St. Helens confirms that eruptions can be foreseen in time to mitigate hazards and save lives. Tools and expertise now exist to provide warning of most volcanic eruptions and to permit accurate prediction. The science of eruption prediction is still in its infancy, but in our opinion it has matured to the point where the primary obstacles to reducing losses from future eruptions are socioeconomic, not scientific ones.

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2. D. A. Swanson, T. J. Casadevall, D. Dzurisin, S. D. Malone, C. G. Newhall, C. S. Weaver, *Science* **221**, 1369 (1983).
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4. Leveling surveys have shown that the crater floor is uplifted prior to eruptions and subsides during eruptions. We therefore equate tilt away from the dome with uplift and tilt toward the dome with subsidence.
5. A frequently used measure of ground deformation at active volcanoes is the microradian or

57.3 × 10^{-6} degree. A vertical change of 1 mm over a horizontal distance of 1 km corresponds roughly to 1 μrad.
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10. This magma source probably lies less than 1 km beneath the crater floor, because measurable deformation occurs within only a few hundred meters of the dome [P. W. Lipman, D. R. Norton, J. E. Taggart, Jr., E. L. Brandt, E. E. Engleman, *U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 631].

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Gas Emissions and the Eruptions of Mount St. Helens Through 1982

Abstract. *The monitoring of gas emissions from Mount St. Helens includes daily airborne measurements of sulfur dioxide in the volcanic plume and monthly sampling of gases from crater fumaroles. The composition of the fumarolic gases has changed slightly since 1980: the water content increased from 90 to 98 percent, and the carbon dioxide concentrations decreased from about 10 to 1 percent. The emission rates of sulfur dioxide and carbon dioxide were at their peak during July and August 1980, decreased rapidly in late 1980, and have remained low and decreased slightly through 1981 and 1982. These patterns suggest steady outgassing of a single batch of magma (with a volume of not less than 0.3 cubic kilometer) to which no significant new magma has been added since mid-1980. The gas data were useful in predicting eruptions in August 1980 and June 1981.*

In addition to the monitoring of volcanic seismicity and ground deformation, regularly scheduled monitoring of gas emissions is a part of the surveillance program at Mount St. Helens. Gas emission monitoring includes daily measurements of plume gases that emanate from the crater and monthly sampling and rapid analyses of gases from crater fumaroles. Data on the chemistry and the emission rates of gases and their evolution with time have been used in forecasting eruptive behavior (*1*) and in inferring conditions within the magma chamber (*2, 3*). Changes in the concentrations of gases and their rates of emission indicate the extent to which volatiles have been removed from the magma and the energy available to power gas-driven volcanic activity. We report here the results and a preliminary interpretation of gas-monitoring studies conducted from mid-1980 through 1982, a period during which 15 eruptions occurred (Table 1).

Volcanic gases at Mount St. Helens are emitted continuously from high-temperature (600° to 890°C) crater fumaroles located either on fissures on the crater floor radiating from the lava dome or on the dome itself. These hot gases rise as a plume that is often sheared off at the crater rim and carried downwind. Fumarolic gases are dominated by water (more than 90 percent), with 1 to 10 percent CO_2 and minor amounts of H_2, H_2S, SO_2, CO, HCl, and HF. From late 1980 through 1981, the concentration of water increased and the concentrations of CO_2 and sulfur gases decreased (Fig. 1; Table 1). Extrapolation of these trends to early June 1980 gives an approximate fumarole gas composition of 90 percent H_2O, 9 percent CO_2, 0.5 percent H_2, and 0.5 percent SO_2 at an extrapolated temperature of 865°C (*4*). The magmatic gases of the catastrophic 18 May 1980 eruption probably contained a minimum of 10 percent CO_2. The steady trends in fumarole gas compositions suggest that there has been no significant addition of new magma to the shallow magma reservoir since mid-1980.

Since September 1980, fumarole gases have had oxygen fugacities close to those of Ni–NiO buffer (± 1/3 logarithmic unit), while the collection temperatures have decreased gradually from greater than 830°C to as low as 600°C (*5*). By comparison, the temperature of the melt, as indicated by the composition of coexisting iron-titanium oxides, averaged about 990°C in 1980 and was about 920°C by early 1982, whereas the oxygen fugacity of the melt, determined from iron-titanium oxides, remained about 1 logarithmic unit greater than that of Ni–NiO (*6*).

Airborne monitoring of SO_2 began on 29 March 1980 (*2, 7*). From early July 1980 through September 1981, CO_2 was also measured (*3*) until the emission rates decreased below the detection limit of 1000 metric ton/day. From these measurements we have established average daily emission rates for SO_2 and CO_2. The emission rates decreased rapidly in 1980 and decreased gradually through 1981 and 1982 (Fig. 2). On the basis of the different rates of outgassing (Table 1), we recognize three periods of activity since the eruption of 18 May 1980 (Table 1). During period 1, from 26 May until 3 June 1980, the emission rates of SO_2 were less than 250 ton/day. We believe that during this period the magma was too deep to permit the effective separation of a volatile phase except during eruptions. Alternatively, the magma may have been shallower, but, because of its high viscosity, the volatiles dissolved in the magma may have been unable to escape at a rate commensurate with the pressure-depth conditions established since the eruptions of 18 May and 25 May 1980. Period 2 began in early June 1980, when the emission rate increased roughly fivefold (*2*). This period of high rates of gas emission was followed by a steady decrease through the remainder of 1980. The increase in early June coincided with the end of inflation of the volcanic edifice, as detected by geodetic measurements and borehole tiltmeter

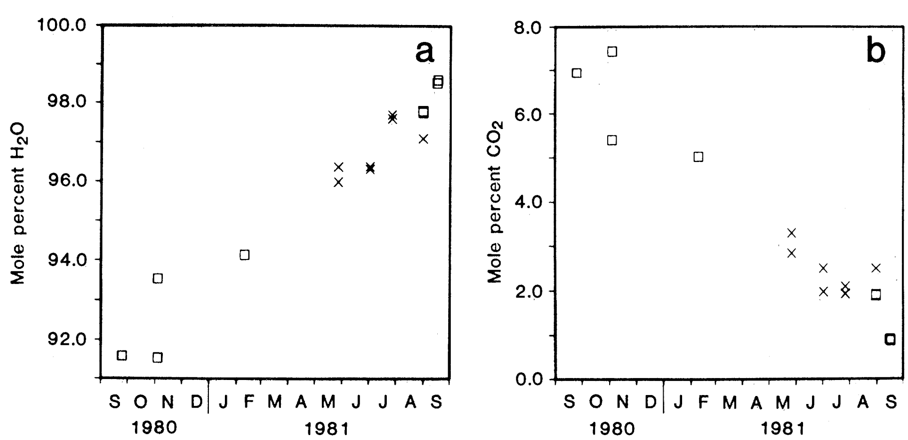

Fig. 1. Mole percentages of H_2O and CO_2 for September 1980 through October 1981. Squares represent complete analyses obtained with a field gas chromatograph or analyses of gases collected in caustic soda solution; x's represent analyses of noncondensable gases with the H_2O content of the gas calculated by the methods of Gerlach and Casadevall (*13*).