57.3 × $10^{-6}$ degree. A vertical change of 1 mm over a horizontal distance of 1 km corresponds roughly to 1 μrad.
6. R. B. Waitt, Jr., *et al.*, *Science* **221**, 1394 (1983).
7. W. T. Kinoshita, D. A. Swanson, D. B. Jackson, in *Physical Volcanology*, vol. 6 of *Developments in Solid Earth Geophysics*, L. Civetta, P. Gasparini, G. Luongo, A. Rapolla, Eds. (Elsevier, Amsterdam, 1974), p. 87.
8. O. Sigurdsson, *J. Geophys.* **47**, 154 (1980).
9. D. D. Pollard, P. T. Delaney, W. A. Duffield, E. T. Endo, A. T. Okamura, *Tectonophysics* (Elsevier, Amsterdam, 1983), vol. 94, p. 541.
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].

26 January 1983; revised 27 June 1983

## 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

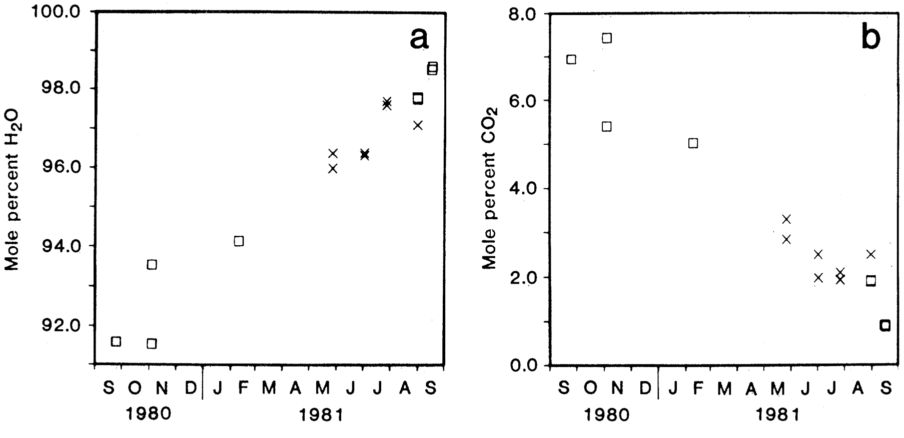

Fig. 1. Mole percentages of $H_2O$ and $CO_2$ for September 1980 through October 1981. Squares represent complete analyses obtained with a field gas chromatograph or analyses of gases collected in caustic soda solution; x's represent analyses of noncondensable gases with the $H_2O$ content of the gas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

data (*8*). We interpret this sudden increase in emission rates as indicating the formation of a separate volatile phase due to decompression of the magma during its ascent. With the accumulation of a separate volatile phase in the roofward portions of the shallow reservoir, the magma lost its buoyant lift and ascent ceased. During period 3, from December 1980 to the present, the rates of gas emission have decreased gradually. The gases now escaping appear to be those produced during the late stages of shallow magma emplacement. During each eruption in 1981 and 1982, gas emissions increased by two to four times the levels measured between eruptions (Table 1). The elevated levels during each eruption are due to the decompression of smaller batches of magma as they ascend from the shallow reservoir.

We interpret these patterns to be an indication of the energy still available in the shallow reservoir of magma. Emission rates of $SO_2$ and $CO_2$ from June to December 1980 were higher than since then (Fig. 2). These changes correspond well with the observed eruptive style of the volcano (Table 1). The eruptions from June through October 1980 were explosive; three eruptions were followed by the extrusion of viscous lava. During 1981 and 1982, gas emission rates decreased and eruptions consisted of predominantly nonexplosive extrusions of lava that progressively formed a dome. The correlations among eruption style, rates of gas emission, and changes in fumarole gas compositions suggest the gradual depletion of volatiles in the magma reservoir.

Gas emission data have been used to successfully predict both an explosive eruption and a nonexplosive eruption (*1*). Several days before the explosive eruption of 7 August 1980, $CO_2$ emissions decreased significantly. A similar pattern prior to the 22 July 1980 explosive eruption was interpreted (*3*) as reflecting a partial sealing of the magma chamber and the subsequent increase in its internal gas pressure. In contrast, 4 weeks before the nonexplosive June 1981 eruption, the rate of $SO_2$ emission began to increase. (The $CO_2$ record for this period was incomplete.) We interpreted this pattern as due to the increased outgassing that accompanies the slow ascent and decompression of a volume of magma with no buildup of gas pressure. We have not observed similar patterns before other eruptions in 1980 through 1982. We have learned that the application of gas emission data to eruption prediction depends critically on the frequency of measurements. Inclement weather interferes with a regular schedule of measurements, especially during the winter and early spring. Gas samples from fumaroles are collected once a month, too infrequently to provide data useful for forecasting eruptive behavior.

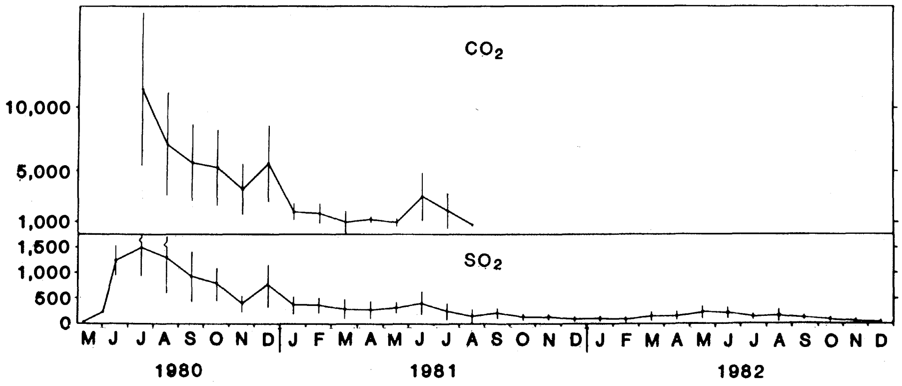

Fig. 2. Emission rates of $CO_2$ and $SO_2$ (in metric tons per day) from March 1980 through December 1982. The average daily emission rate was calculated for each month. Thin vertical lines indicate 1 standard deviation.

Table 1. Sulfur dioxide emissions from Mount St. Helens from mid-1980 through 1982.

| Dates | | Explosive with pyroclastic flows | Lava extrusion | $SO_2$ emission rates between eruptions (ton/day) | $SO_2$ maximum rate during eruption (ton/day) | Interval since start of previous eruption (days) |
|---|---|---|---|---|---|---|
| | | *1980* | | | | |
| 18 May | Period 1 | x | | 0 | | |
| 25 May | | x | | 200 | 2600* | 7 |
| 12 June | Period 2 | x | x | 1000 | | 18 |
| 22 July | | x | | 1500 | | 40 |
| 7 August | | x | x | 1300 | | 16 |
| 16 to 18 October | | x | x | 1000 | 1400 | 70 |
| 27 December to 3 January | Period 3 | | x | 400 | | 72 |
| | | *1981* | | | | |
| 5 to 6 February | | | x | 300 | 620 | 40 |
| 10 to 12 April | | | x | 300 | | 64 |
| 18 to 19 June | | | x | 250 | 900 | 69 |
| 6 to 10 September | | | x | 160 | 660 | 80 |
| 30 October to 6 November | | | x | 135 | 230 | 55 |
| | | *1982* | | | | |
| 19 March to 8 April | | † | x | 115 | 650‡ | 132 |
| 14 to 20 May | | | x | 160 | 640 | 56 |
| 18 to 23 August | | | x | 140 | 530 | 96 |

*Measured during the waning phase of the eruption. †Explosion on 19 March produced a small (less than 0.0001 $km^3$) deposit of pumice. ‡Measured on 5 April 1982.

The textural and chemical homogeneity of rock erupted during 1980 through 1982 (*9*) suggests that it came from a single reservoir of magma that was emplaced at shallow depth between late March and early June 1980 (*2*). The emission rate data for $SO_2$ were used to calculate that approximately 0.9 $km^3$ of magma was outgassed with respect to sulfur since late May 1980 (*10*). The volume of sulfur released during the 18 May 1980 eruption is estimated at between $0.24 \times 10^{12}$ g (*11*) and $1.1 \times 10^{12}$ g (*12*). Including the sulfur released on 18 May 1980 in the volume calculation increases the volume of magma outgassed to between 1.8 and 5.0 $km^3$. The total volume of rock erupted since 18 May 1980 is approximately 0.3 $km^3$. This implies that most of the sulfur gas emissions are from magma intruded beneath the volcano. Our estimate is conservative and is based on the assumption that the emitted sulfur gases represent the efficient, homogeneous outgassing of the entire body of magma. A likely model is that magma at the top of the shallow reservoir is more completely degassed than material in the roots of the reservoir, where confining pressures are higher.

Addition of new magma or new volatiles to the shallow reservoir could be a source of additional gas emissions released to the atmosphere. Such a change in the activity of Mount St. Helens should be recognizable in terms of an increase in the rates of gas emission and in a change in gas composition.

T. CASADEVALL
*U.S. Geological Survey,*
*Cascades Volcano Observatory,*
*Vancouver, Washington 98661*
W. ROSE
*Michigan Technological University,*
*Houghton 49931*
T. GERLACH
*Sandia National Laboratories,*
*Albuquerque, New Mexico 87185*
L. P. GREENLAND
*U.S. Geological Survey,*
*Hawaiian Volcano Observatory,*
*Hawaii National Park 96718*
J. EWERT
*U.S. Geological Survey,*
*Cascades Volcano Observatory*
R. WUNDERMAN
*Michigan Technological University*
R. SYMONDS
*U.S. Geological Survey,*
*Cascades Volcano Observatory*

### References and Notes

1. T. Casadevall, W. Rose, J. Ewert, D. Harris, *Eos* **63**, 174 (1982).
2. T. Casadevall *et al.*, *U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 193; *Eos* **62**, 1088 (1981).
3. D. Harris, M. Sato, T. J. Casadevall, W. Rose, T. J. Bornhorst, *U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 201.
4. T. Casadevall and P. Greenland, *ibid.*, p. 221.
5. T. Gerlach and T. Casadevall, unpublished data.
6. W. Melson and C. Hopson, *U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 641; W. Melson, personal communication.
7. Airborne $SO_2$ measurements are made with a correlation spectrometer (COSPEC); an infrared spectrophotomer (MIRAN 1A) is used for $CO_2$ measurements (*2, 3*). For each technique a concentration profile (for $CO_2$) or a concentration path-length profile (for $SO_2$) is obtained from a fixed-wing aircraft flying under the plume (for $SO_2$) or through the plume (for $CO_2$). The product of the path-length concentration (in parts per million–meters), the plume width (in meters), and the plume velocity (in meters per second), which is the emission rate of the gas (in parts per million per cubic meter per second), is reported as metric tons per day.
8. J. Dvorak, A. T. Okamura, C. Mortensen, M. J. S. Johnston, *U.S. Geol. Surv. Prof. Pap. 1250* (1981), p. 169; D. Swanson, P. W. Lipman, J. G. Moore, C. C. Heliker, K. M. Yamashita, *ibid.*, p. 157.
9. P. Lipman, D. R. Norton, J. E. Taggart, E. L. Brandt, E. E. Engleman, *ibid.*, p. 631; K. V. Cashman and J. E. Taggart, *Science* **221**, 1385 (1983).
10. From 26 May 1980 through December 1982, $2.1 \times 10^{11}$ g of sulfur was emitted from the volcano; 80 percent was as $SO_2$, and an estimated 20 percent was as $H_2S$ [P. V. Hobbs, L. F. Radke, M. W. Eltgroth, D. A. Hegg, *Science* **211**, 816 (1981)]. The preeruption sulfur content of the melt has been determined from melt inclusions to be 100 ppm [H. Sigurdsson, *Eos* **63**, 601 (1982)], whereas the posteruption concentration of sulfur in the 1980 and 1982 eruptive products is 20 ppm (H. Sakai, personal communication; W. Rose, unpublished data).
11. R. Stoiber *et al.*, *J. Volcanol. Geothermal Res.* **11**, 203 (1981).
12. M. Millan, personal communication.
13. T. Gerlach, *J. Volcanol. Geothermal Res.* **6**, 165 (1979); ———— and T. Casadevall, in preparation.

14. We acknowledge helpful reviews of this report by R. Fournier, J. Eichleberger, and two anonymous referees. One of us (T.G.) was supported by the Department of Energy under contract DE-AC04-76DP00789. Sandia National Laboratories is a Department of Energy facility.

26 January 1983; revised 22 June 1983

# Petrologic Monitoring of 1981 and 1982 Eruptive Products from Mount St. Helens

Abstract. *New material from the dacite lava dome of Mount St. Helens, collected soon after the start of each successive extrusion, is subjected to rapid chemical and petrologic analysis. The crystallinity of the dacite lava produced in 1981 and 1982 is 38 to 42 percent, about 10 percent higher than for products of the explosive 1980 eruptions. This increase in crystallinity accompanies a decrease in the ratio of hornblende to hornblende plus orthopyroxene, which suggests that the volatile-rich, crystal-poor material explosively erupted in 1980 came from the top of a zoned magma chamber and that a lower, volatile-poor and crystal-rich region is now being tapped. The major-element chemistry of the dacite lava has remained essentially constant (62 to 63 percent silica) since August 1980, ending a trend of decreasing silica seen in the products of the explosive eruptions of May through August 1980.*

Six mainly explosive eruptions of Mount St. Helens in 1980 were followed by nine mainly nonexplosive eruptions in 1981 and 1982, each of which has added a new lobe of viscous dacite to the dome that occupies the inner floor of the crater. Each episode of dome growth has lasted 2 to 7 days and has added to the dome between $2.5 \times 10^6$ and $5 \times 10^6$ m$^3$ of new material (*1*). Dome growth occurs in part as a result of the injection of magma into the dome (*2*), but most new material is added as viscous lava extruded from a central conduit.

Samples were collected during or just after each new extrusive event, and major elements were analyzed within a week by x-ray fluorescence techniques; minor elements were analyzed later by induction-coupled plasma methods (*3*); and we carried out modal analyses of new samples by counting a minimum of 1000 points per section, with a minimum of three samples per lobe. Chemical and petrologic analyses serve to check the continued homogeneity of the dome lava, and they also provide constraints on models of the system. In addition, compositional changes may precede or accompany changes in the eruptive behavior of the volcano.

The flow morphology of the dacite lava changes in the course of each eruption. Lava less than 24 hours old has a smooth, coherent surface. As the lava moves downslope and its rate of movement decreases (*2*), its surface becomes rough and fragmented, a scoriaceous carapace forms, and arcuate flow lines commonly develop parallel to the leading edge of the flow. The rate of extrusion and downslope velocity probably control the extent of fragmentation of the new lobe and thus its morphology.

The flow surface of each lobe is vesicular material, which forms a scoriaceous carapace. Samples from the interior of the flow are far denser than those from the vesicular veneer. Most samples from the interior exhibit flow banding, with alternating layers of dense and vesicular dacite. Bands 1 to 50 cm wide extend laterally as much as 30 m. The long axes of xenoliths, which comprise 2 to 3 percent of the lavas (*4*), are commonly aligned parallel to the visible banding and are surrounded by aureoles of extreme vesiculation. The banding and vesiculation suggest shear during migration of the viscous magma to the surface.

Analyses of samples from 1980 and early 1981 dome lavas suggested that chemical variation in any one dome lobe was comparable to the variation between samples from separate lobes. We tested the heterogeneity of an individual lava flow by detailed sampling of the December 1980 lobe. Three or four samples were collected from each of ten sites on the south margin of the lobe. Although hand specimens vary notably in glass content and vesicularity, standard deviations for 16 chemical analyses from the December 1980 lobe are generally less

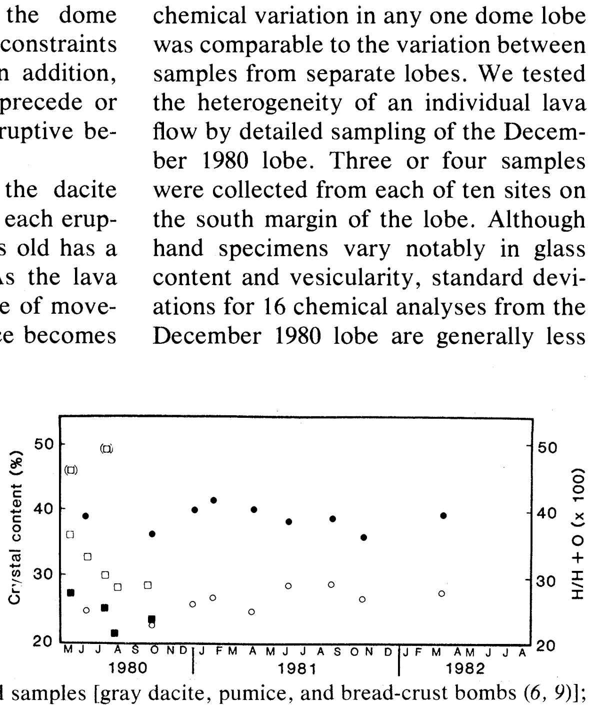

Fig. 1. Plots of crystallinity (filled symbols) and ratio of hornblende to hornblende + orthopyroxene (H/H + O) (open symbols) for Mount St. Helens eruptive products. Point counts were recalculated to 100 percent on a vesicle-free basis to allow comparison between scoriaceous and relatively dense samples; (■) explosively erupted samples [gray dacite, pumice, and bread-crust bombs (*6, 9*)]; (●) average analyses for each dome lobe.