should be recognizable in terms of an increase in the rates of gas emission and in a change in gas composition.

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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.
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10. From 26 May 1980 through December 1982, 2.1×10^{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concentration of sulfur in the 1980 and 1982 eruptive products is 20 ppm (H. Sakai, personal communication; W. Rose, unpublished data).
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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 2.5×10^6 and 5×10^6 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

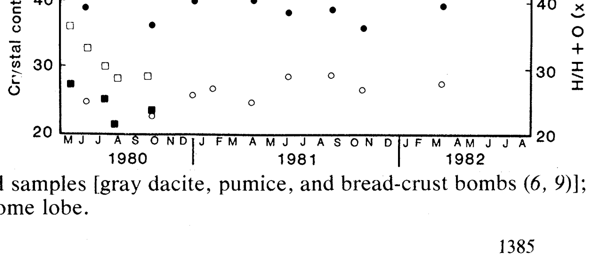

Fig. 1. Plots of crystallinity (filled symbols) and ratio of hornblende to hornblende + orthopyroxene (H/H + O) (open symbols) for Mount St. Helens eruptive products. Point counts were recalculated to 100 percent on a vesicle-free basis to allow comparison between scoriaceous and relatively dense samples;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

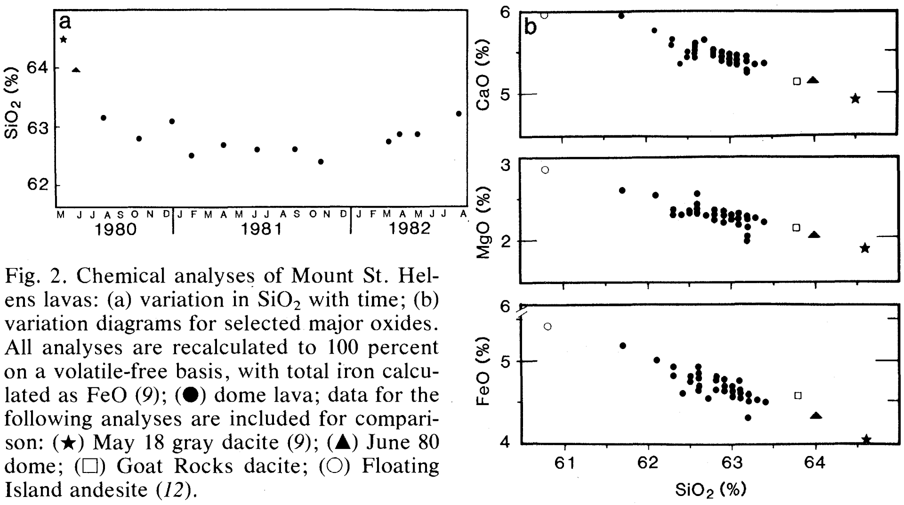

Fig. 2. Chemical analyses of Mount St. Helens lavas: (a) variation in SiO_2 with time; (b) variation diagrams for selected major oxides. All analyses are recalculated to 100 percent on a volatile-free basis, with total iron calculated as FeO (*9*); (●) dome lava; data for the following analyses are included for comparison: (★) May 18 gray dacite (*9*); (▲) June 80 dome; (□) Goat Rocks dacite; (○) Floating Island andesite (*12*).

than 3 percent, a variation comparable to that observed between samples from all dome lobes (Table 1).

The dome lavas erupted from Mount St. Helens in 1981 and 1982 are porphyritic dacite, with phenocrysts of plagioclase (32 percent), orthopyroxene (4.5 percent), hornblende (1.5 percent), magnetite-ilmenite (2 percent), and minor clinopyroxene (< 0.5 percent). The groundmass (comprising the remaining 60 percent of the total rock) contains microphenocrysts of plagioclase with minor amounts of orthopyroxene and ferromagnesian minerals in a glassy matrix. Zoned, euhedral plagioclase laths 0.5 to 2 mm long contain glass inclusions either along zone boundaries or scattered in the interior of the crystals. Most euhedral hypersthene crystals (< 0.5 mm) have inclusions of magnetite and ilmenite. The rims of elongate subhedral hornblende crystals (0.5 to 1 mm) are oxidized and commonly have partially reacted with the melt to form rims of plagioclase + pyroxene + magnetite. Crystal aggregates are common; they may represent cognate cumulates or the products of disintegration of included xenoliths. Rare olivine crystals with well-developed reaction rims and large (> 2 mm) plagioclase phenocrysts with spongy subhedral cores and euhedral inclusion-free rims are almost certainly xenocrysts. The crystallinity of the dome lavas (as determined by point counts of phenocrysts) averages 40 to 45 percent and has not changed significantly since June 1980; this value approaches an upper limit beyond which magma can no longer flow to the surface because of its high viscosity (*5*). Groundmass crystallinity has not been determined quantitatively, but it is greater than observed in 1980 bread-crust bombs and gray dacite.

The pumice that erupted explosively in 1980 contains the same phenocryst phases as the 1981 and 1982 dome lavas (*6*). Dome lavas differ from the products of 1980 explosive eruptions in crystallinity, in the ratio of hornblende to hornblende + orthopyroxene (H/H + O) (Fig. 1), and in groundmass texture. The pumice, bread-crust bombs, and gray dacite of the 1980 explosive eruptions have a crystallinity of about 30 percent and an H/H + O ratio of between 0.32 and 0.50; their glassy groundmass includes flow-aligned microlites of plagioclase. In contrast, dome lavas of 1980 through 1982 have a crystallinity of 40 percent and an H/H + O ratio averaging 0.25, in addition to a more coarsely crystalline groundmass. The groundmass plagioclase of the dome lava is larger than that of the explosive eruption products, is more tabular in shape, and exhibits no flow-induced orientation. This difference in groundmass texture probably results from the difference in the modes of eruption (and resultant difference in cooling rate) of the two groups. The increased phenocryst content and lower H/H + O ratio in the dome lava suggest that the magma chamber was zoned, with a relatively volatile-rich, crystal-poor cap that produced the explosive products of 1980 overlying a volatile-poor, crystal-rich interior (the dome lava). That the eruptive products of Mount St. Helens originate in a zoned magma chamber was suggested in 1980 by petrographic studies of pumice deposits (*6*) and microprobe analyses of melt inclusion glasses (*7*). Additional evidence provided by microprobe analyses of plagioclase and hornblende crystals from samples of the June 1980 dome suggest the existence of two chemically distinct source magmas (*8*), whereas iron-titanium oxide pairs from flow-banded pumice indicate that equilibrium temperatures for the dark and light pumice bands may have been different (*8*).

Although the chemical composition of the dome lava is slightly heterogeneous in detail, numerous major-element analyses show that it has remained essentially constant since December 1980 (Table 1, Fig. 2a). This overall homogeneity of the

Table 1. Chemical composition (in percentages) of Mount St. Helens dome samples, May 1980 through May 1982. Abbreviations: *N*, number of samples; LOI, loss on ignition.

Date	*N*	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI
18 May 1980 dacite*	1	63.50	17.80	4.80	2.10	5.12	4.45	1.29	0.60	0.14	0.07	0.09
August 1980†	1	62.70	17.80	5.06	2.26	5.42	4.41	1.23	0.67	0.14	0.07	0.14
October 1980	4	62.40	18.00	5.14	2.31	5.55	4.45	1.20	0.67	0.15	0.07	0.14
December 1980	16	62.70	17.90	5.09	2.26	5.39	4.44	1.25	0.68	0.14	0.07	0.04
February 1981	3	62.30	17.90	5.40	2.44	5.51	4.51	1.24	0.70	0.15	0.08	0.25
April 1981	4	62.20	17.80	5.32	2.37	5.49	4.42	1.24	0.71	0.15	0.08	0.13
June 1981	4	62.20	17.90	5.32	2.38	5.52	4.44	1.25	0.70	0.15	0.08	0.08
September 1981	3	62.00	17.90	5.24	2.26	5.48	4.54	1.25	0.68	0.16	0.08	0.12
October 1981	3	61.60	18.20	5.13	2.29	5.33	4.48	1.25	0.67	0.15	0.08	0.07
March 1982 pumice	2	62.40	17.90	5.30	2.28	5.48	4.50	1.28	0.70	0.16	0.08	0.02
March 1982	2	62.40	17.80	5.34	2.29	5.55	4.36	1.27	0.72	0.16	0.08	< 0.01
April 1982	2	62.70	17.90	5.04	2.18	5.42	4.46	1.29	0.67	0.15	0.07	< 0.01
May 1982	1	62.50	17.80	5.28	2.27	5.40	4.42	1.28	0.72	0.16	0.08	< 0.01
August 1982	1	63.10	17.70	4.99	1.94	5.24	4.55	1.36	0.69	0.15	0.07	0.03

*Sample from C. D. Miller, reanalyzed in November 1981. †Sample from P. Lipman, reanalyzed in November 1981.

dome lavas contrasts with the decreasing silica content of the products of the explosive activity during 1980 (*9*). In all eruptions where dome growth has followed explosive activity, including the March 1982 eruption (Table 1), the major-element chemistry of the dome lava has been identical to that of the accompanying explosive products (*9*). This similarity suggests that both types of activity result from the movement to the surface of a single body of magma; we envision a small plug ascending in a conduit, where magma high in the column is slightly more volatile-rich (that is, explosive) than the material lower down.

Major-element variation diagrams for 1981 and 1982 dome lavas show trends similar to those of the 1980 products (*9*). The lack of chemical variation since 1980 suggests that all eruptions are being generated from a single, relatively homogeneous magma body, probably at a depth of only 1 to 2 km (*10*). The results of analyses of emitted gases suggest that its volume exceeds 0.3 km^3 (*11*). Because the trend since the end of 1980 has been toward the eruption of more homogeneous material, it seems that chemical and mineralogic variations of the June 1980 "mixed magmas" (*7, 8*) were most likely caused by the mixing of pockets of remnant-evolved magma from the 18 May 1980 eruption. Seismic data (*10*) suggest that new material may have been intruded at depth during the activity of March 1982. Petrologic data, however, indicate that, if such an intrusion occurred, either this new material has not yet reached the surface or it is identical to material already residing in the shallow chamber.

The results of analyses of solid products of the last eruptive episode [the 19th century Floating Island andesite and Goat Rocks dacite (*12*)] lie along trends delineated by the 1980 lavas (Fig. 2b). This correspondence supports the suggestion (*9*) that the activity for 1980 through 1982 represents continued evolution of the magma body that caused the eruptions of the past few centuries. Although on the basis of past eruptive episodes a declining SiO_2 content might be expected as a trend for future activity (*12*), there is no evidence for the continuation of the trend toward lower-SiO_2 magma initiated in 1980 (*9*). In short, the chemical homogeneity of recently erupted materials suggests that the shallow magma system has reached a temporary steady state that will probably continue for the near future. The simplest model to account for such a steady state involves a slowly cooling and crystallizing body of magma. Volatiles concentrated in the melt during this process may sufficiently decrease the density of part of this body to drive the sporadic rise of some of this material to the surface (*11*).

Petrologic changes in eruptive products have been monitored at Bezymianny volcano in Kamchatka; lavas from the Bezymianny dome Novy were chemically homogeneous over 20 years (1956 through 1976) of periodic dome growth, while exhibiting distinct changes in crystallinity, both in the ratios of phenocryst phases and in the development of second-generation phenocrysts (*13*). In 1976, a decrease in the SiO_2 content of the Bezymianny dome lava accompanied a change in eruptive products.

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Monitoring the 1980–1982 Eruptions of Mount St. Helens: Compositions and Abundances of Glass

Abstract. *The Mount St. Helens eruptive sequence of 1980 through 1982 reflects the tapping of successively less water-rich, more highly crystallized, and more viscous, highly phyric dacitic magmas. These changes reflect both syn- and preeruption processes. The decreasing water content points to a continued decline in the volume and intensity of explosive pyroclastic activity. This decreasing water content appears to be composed of a long-term trend established during a long period of repose (about 130 years) imposed on short-term trends established during short periods (about 7 to 100 days) of repose between eruptions in the present eruptive cycle. The last two eruptive cycles of this volcano, the T (A.D. 1800) and W cycles (about A.D. 1500), exhibited similar trends. These changes are inferred from a combination of petrographic, bulk chemical, and electron- and ion-microprobe analyses of matrix and melt-inclusion glasses.*

The dacitic to andesitic eruptions of Mount St. Helens in 1980 through 1982 are characterized by short periods of activity, lasting a few days, separated by much longer periods of quiescence, characterized by ongoing volatile emissions. The mode of eruption has changed in a systematic way and can be divided into five phases (Table 1). These phases form a convenient framework in which to view (i) the changes in the extent of crystallization, (ii) the inferred H_2O contents of matrix and melt-inclusion glasses, and (iii) the preeruption H_2O contents of the bulk magma.

I focus here on the use of compositional changes in the matrix glasses of the eruptive products and melt inclusions in crystals and in the bulk rocks as a tool in volcano monitoring. Glasses in the matrix and in melt inclusions show systematic changes in composition with time. Melt inclusions provide unique information on preeruption volatile compositions and are a guide to preeruption magma compositions. The pyroclastic samples provide material that erupted from some depth and then was rapidly quenched. They furnish insight into the state of the magma chamber prior to eruption. Dome samples, on the other hand, reflect a slower and shallower emplacement process, resulting in a longer cooling history and more extensive degassing. The highly phyric nature of even the least crystalline samples (40 percent crystals) reflects extensive preeruption (intratelluric) crystallization. The glasses have evolved to their final eruption composition through a combination of cool-