Overview

Basic facts of the 2004–2006, and continuing, eruption of Mount St. Helens, Washington

Early unrest

Seismic swarm onset	September 23, 2004, 0200 hr Pacific daylight time (PDT)
First explosion	October 1, 2004, 1202 hr PDT
Lava extruded to surface	October 11, 2004 (not observed because of poor weather but deduced subsequently)

Explosions

Number of explosions	6
Volcano explosivity index (VEI)	1–2 for early October 2004 vent-forming explosions
Largest VEI	2 (Oct. 5, 2004; Mar. 8, 2005)
Maximum known height of eruption clouds	11 km according to pilot reports 6 km minimum by Doppler radar (NEXRAD), March 8, 2005

Gases

Sulfur dioxide, maximum	240 tons per day (Oct 27, 2004)
Carbon dioxide, maximum	2,415 tons per day (Oct 7, 2004)

Lava dome

Composition	Dacite, 65% SiO_2
Phenocrysts	Plagioclase, amphibole, hypersthene
Total volume extruded	About 95×10^6 m^3 (as of September 11, 2007)
Maximum thickness of new dome	450 m
Highest altitude measured for new dome	2,368 m above sea level (spine 5, July 2005)
Volcano's summit (crater rim highest point)	2,540 m above sea level
Most notable rock avalanche	May 30, 2006, starting volume 50,000–100,000 m^3

Crater Glacier

Volume before eruption	80×10^6 m^3
Volume after eruption	74×10^6 m^3
Maximum thickness of glacier	2004: about 150 m (datum is 1986 glacier surface) April 2005–July 2007: about 240 m, east arm, (deformed upper surface)

Monitoring sites within 10 km of volcano on September 22, 2004 (before onset)

Seismometers	8
GPS receivers	1
Fixed transmitting cameras	1 (Gifford Pinchot National Forest)
Borehole tiltmeters	0

Number of monitoring sites installed within 10 km, September 2004–January 2008

Seismometers (includes accelerometers)	20 (some destroyed or removed)
GPS receivers	20 (includes 14 installed by PBO *)
Fixed cameras	8
Tiltmeters	9 (includes 4 installed by PBO)
Borehole strainmeters	2 (installed by PBO)

Spiders

Number deployed to crater for GPS or seismic monitoring	31
Number lost to natural causes	9

* Plate Boundary Observatory, a research component of EarthScope, which is sponsored by the National Science Foundation.

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A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006
Edited by David R. Sherrod, William E. Scott, and Peter H. Stauffer
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Chapter 1

Overview of the 2004 to 2006, and Continuing, Eruption of Mount St. Helens, Washington

By William E. Scott[1], David R. Sherrod[1], and Cynthia A. Gardner[1]

Abstract

Rapid onset of unrest at Mount St. Helens on September 23, 2004, initiated an uninterrupted lava-dome-building eruption that continues to the time of writing this overview (spring 2006) for a volume of papers focused on this eruption. About three weeks of intense seismic unrest and localized surface uplift, punctuated by four brief explosions, constituted a vent-clearing phase, during which there was a frenzy of media attention and considerable uncertainty regarding the likely course of the eruption. The third week exhibited lessened seismicity and only minor venting of steam and ash, but rapid growth of the uplift, or welt, south of the 1980–86 lava dome proceeded as magma continued to push upward. Crystal-rich dacite (~65 weight percent SiO_2) lava first appeared at the surface on October 11, 2004, beginning the growth of a complex lava dome of uniform chemical composition accompanied by persistent but low levels of seismicity, rare explosions, low gas emissions, and frequent rockfalls. Petrologic studies suggest that the dome lava is chiefly of 1980s vintage, but with an admixed portion of new dacite. Alternatively, it may derive from a part of the magma chamber not tapped by 1980s eruptions. Regardless, detailed investigations of crystal chemistry, melt inclusions, and isotopes reveal a complex magmatic history.

Largely episodic extrusion between 1980 and 1986 produced a relatively symmetrical lava dome composed of stubby lobes. In contrast, continuous extrusion at mean rates of about 5 m^3/s in autumn 2004 to <1 m^3/s in early 2006 has produced an east-west ridge of three mounds with total volume about equal to that of the old dome. During much of late 2004 to summer 2005, a succession of spines, two recumbent and one steeply sloping and each mantled by striated gouge, grew to nearly 500 m in length in the southeastern sector of the 1980 crater and later disintegrated into two mounds. Since then, growth has been concentrated in the southwestern sector, producing a relatively symmetrical mound with steep gouge-covered slabs on its east flank. Throughout the eruption, the position of the extrusive vent has remained more or less fixed. Lack of geodetic evidence for either volume increase or pressure increase in the deep magmatic system since about 1990 and geodetic modeling that can account for only 20 to 30 percent of the 2004-to-present dome volume puzzles geodesists. Better constraints on parameters such as magma-chamber volume, crustal properties, and magma compressibility are needed to improve the models.

Development of the welt and the new dome bisected horseshoe-shaped Crater Glacier, which formerly wrapped around three sides of the 1980s dome, and fractured, compressed, and thickened the glacier's surviving east and west arms. Doubling of ice thickness resulted in increased flow rate and advance of termini, although rapid infiltration of water into the highly porous glacier bed prevented substantial basal sliding. Overall, dome growth and disintegration has removed surprisingly little ice.

The outcome of the ongoing eruption remains uncertain, but Mount St. Helens' varied eruptive history suggests multiple possibilities. One dynamical model and several petrologic investigations regard the current eruption as an extension of 1980s dome building that may persist continuously or episodically for years to come.

Introduction

A commonly asked question in the Pacific Northwest during the past 20 years, "When will Mount St. Helens erupt again?," was answered in late September to early October 2004, when a typical days-long swarm of small earthquakes escalated into intense unrest and eruption (Dzurisin and others, 2005). Many of the widely acknowledged principles of successful volcano-risk mitigation were reinforced:

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- Understand a volcano's eruptive history and have an up-to-date hazard assessment.
- Have adequate monitoring systems installed and a good record of background behavior.
- Have a strong team of scientists and technicians on site, be able to draw on other experienced personnel, and have replacement monitoring equipment available.
- Have an interagency coordination or response plan in place and a working relationship with local emergency-response and land-management agencies.
- Have a well-coordinated joint information center to deliver updates to the media, public officials, and the public.

Fortunately, these conditions were largely met, owing to the volcano's memorable eruption in 1980 (Lipman and Mullineaux, 1981), to long-established monitoring systems operated by the U.S. Geological Survey (USGS) at its David A. Johnston Cascades Volcano Observatory (CVO) and the Pacific Northwest Seismic Network (PNSN) at the University of Washington, and to long-term cooperation in volcano-hazard and risk-mitigation issues by the Gifford Pinchot National Forest (GPNF; in which Mount St. Helens is located), Washington State Military Department–Emergency Management Division, and USGS–CVO. Nonetheless, scientific uncertainty, strong media interest and scrutiny, and the excitement of a volcanic crisis created an intense and, at times, chaotic scene.

As described in the contributions to this volume, more than 18 months of continuous activity has given scientists from the USGS and numerous academic institutions an opportunity to closely study an eruption that has progressed much differently from that of 1980–86. Rapid onset of unrest and eruption, apparently continuous extrusion of gas-poor, mostly crystallized lava into a glacier-filled crater, and month after month of monotonous seismicity, among numerous other observations and surprises, have led to new insights and models of eruptive processes. The eventual duration and outcome of the current eruption remain unknown, but scientists look forward to exploiting the rich research environment that Mount St. Helens continues to provide. Furthermore, the eruption has stimulated the seemingly insatiable interest of the public and media in volcanoes and reinvigorated visitation at the GPNF's Mount St. Helens National Volcanic Monument (herein, the Monument). The result is a more volcano-savvy citizenry in the Pacific Northwest, which is essential for maintaining awareness of potential volcano hazards posed by the other 12 Cascade volcanic centers in the U.S. and the three major Canadian volcanic centers in southern British Columbia.

This overview briefly summarizes the recent eruptive history of Mount St. Helens, including the 1980–86 eruption, the 1986–2004 period of quiescence punctuated by several notable periods of unrest and minor explosions, and the current eruption. Although not addressed in this overview, comparisons of the current eruption to historical dome-building eruptions at other volcanoes are provided in several papers in this volume (Schilling and others, chap. 8; Vallance and others, chap. 9; Cashman and others, chap. 19).

Previous Eruptive History

Mount St. Helens (fig. 1) has been by far the most frequently active volcano in the Cascade Range during the past few thousand years, producing eruptions of a wide variety of types and scales (Hoblitt and others, 1980; Crandell, 1987; Scott, 1989; Mullineaux, 1996; Clynne and others, this volume, chap. 28). Recent work shows that an eruptive center has existed in the Mount St. Helens area for at least 300,000 years. Early dacitic lava domes created a broad volcano surrounded by aprons of pyroclastic and volcaniclastic deposits. Only during the past few thousand years did the volcano grow into the high graceful cone of early 1980. Late Holocene cone building, which followed an apparent dormant period of about 7,000 years, began with several periods of lava-dome and plinian eruptions of dacite, not unlike earlier events in the volcano's history. However, starting about 2,500 years ago, substantial amounts of basalt and andesite began to erupt between dacitic eruptions. Such lava flows buried large parts of a central cluster of dacite domes and flanking fans and started cone building in earnest. Eruptions during the 17th and early 18th centuries raised the cone about 300 m, with emplacement of the summit dacitic lava dome, and added fans of debris on all flanks of the volcano. Eruptions during the early to middle 19th century did not alter the shape of the volcano greatly but provided an opportunity for early settlers to witness several small eruptions and to realize that Mount St. Helens is an active volcano.

1980–1986 Eruption

Although a detailed understanding of Mount St. Helens' eruptive history and a hazard-zonation map were available in spring 1980 (Crandell and Mullineaux, 1978), monitoring of the volcano was minimal (one telemetered seismometer on the west flank and one surveyed electronic-distance-measurement line on the east flank). With no recent eruptions having occurred, local officials and land managers had no experience with volcanic crises. The onset of seismicity in mid-March 1980, which accelerated greatly on March 25, and steam explosions starting on March 27 generated intense interest by public officials and the media. This interest required rapid creation of an emergency coordination center to bring together representatives of key agencies. GPNF's experience in fire operations helped greatly in organizing a response. Scientists learned numerous lessons, especially the need to speak with one voice and to quickly address rumors and conflicts (Miller and others, 1981). During April and early May 1980, a decrease in seismicity and frequency of steam explosions reduced public concern and intensified calls to open closed areas. However, the rapidly growing north-flank bulge, driven by intrusion of a cryptodome into the volcano, kept scientists wary.

Hopes that a distinctive change in seismicity or rapid acceleration of ground deformation would permit a short-term hazard forecast were dashed in minutes on May 18, when the north flank failed in a great debris avalanche (Glicken, 1998). This avalanche was the largest subaerial landslide on Earth in historical time. The resulting rapid decompression of the cryptodome generated explosions that produced a lateral blast, a rapidly moving pyroclastic density current that leveled ~600 km^2 of forest (Hoblitt, 2000) and killed most of the 57 victims of the eruption. The debris avalanche and blast were of a scale unknown in Mount St. Helens' history and proved milestones in the recognition of such events as an important hazard at composite volcanoes worldwide (Siebert, 1984). The hours-long eruption of pumice and ash that followed the blast was of expectable scale, although many affected communities in eastern Washing-

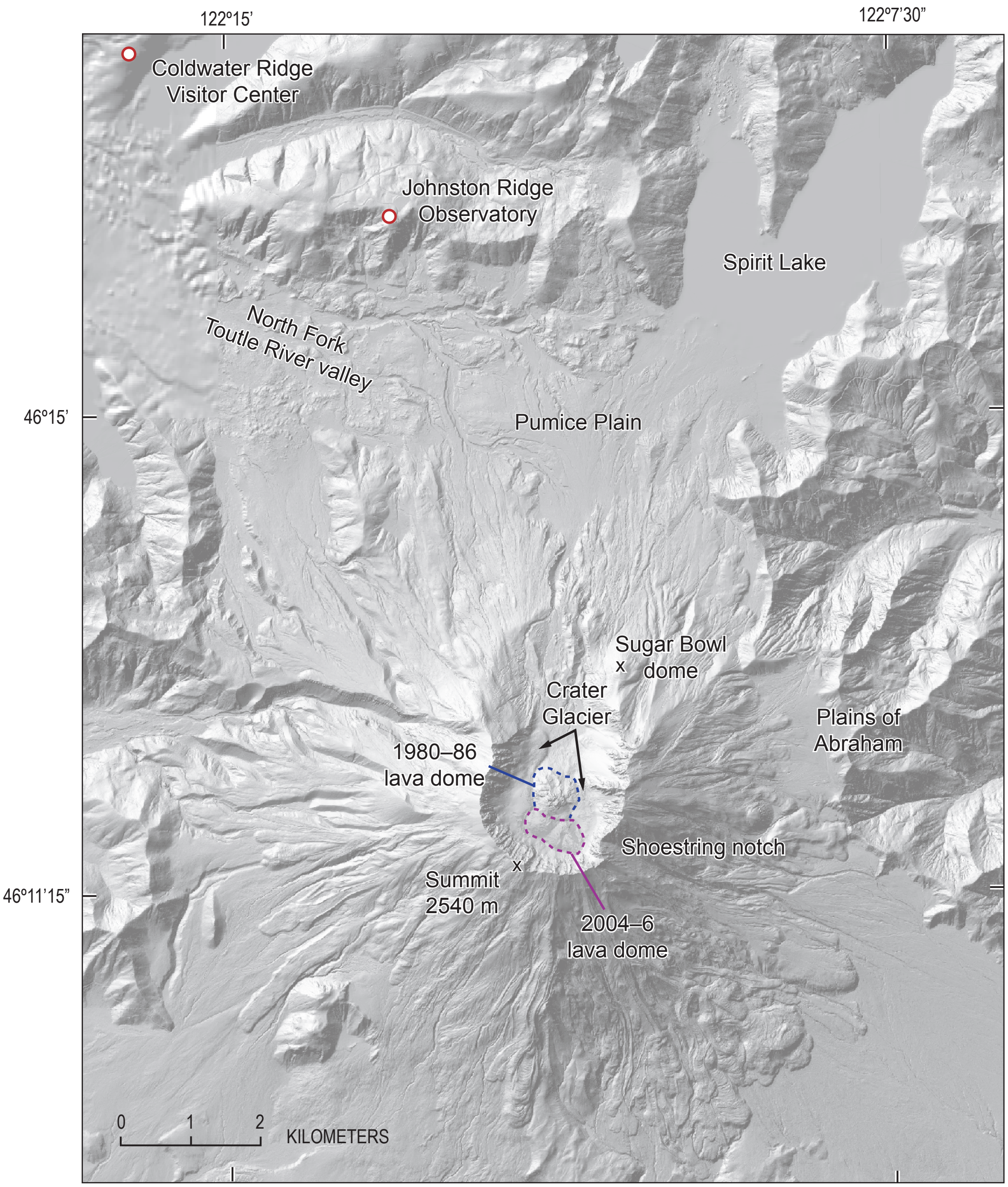

Figure 1. Shaded-relief index map of Mount St. Helens and adjacent areas, showing locations discussed in text. Base is chiefly from digital elevation model (DEM) of 2003 lidar survey (Schilling and others, chap. 8, this volume). Crater features are from DEM made from February 2006 aerial photographs, and northwest corner of map is from the National Elevation Dataset.

ton, northern Idaho, and western Montana were unaware of potential hazards and poorly prepared to respond to tephra fallout and resulting deposits on the order of millimeters to as much as 8 cm thick (Warrick and others, 1981).

Five smaller subplinian eruptions during summer 1980 were preceded by recognizable precursors, as were the 20 lava-dome-building eruptions that ended in October 1986 (Malone and others, 1981; Swanson and others, 1983). Dome-building eruptions were chiefly several-day episodes of extrusion of $1–6\times10^6$ m^3 of lava at average rates as high as 25 m^3/s. Three episodes lasted longer, including one of largely endogenous growth in 1982–83 that lasted 368 days and had an average eruption rate of 0.7 m^3/s. By October 1986, the lava dome stood about 270 m above the 1980 crater floor and had a total volume in the range of 77 to 91×10^6 m^3 (as estimated by Swanson and Holcomb, 1990, and Mills, 1992, respectively).

1986 to 2004

During 1980–86 dome building, seismicity was largely confined to shallow depth (<3 km) and related temporally to periods of extrusion. Starting in 1987, deeper earthquakes became more frequent. Stress-field modeling using focal mechanisms of deep earthquakes supported a hypothesis of pressurization of the magmatic system, which was thought to result from sealing of the shallow conduit (Moran, 1994). By late 1989, deep (3–10 km) seismicity was dominant and, over the next 22 months, 28 shallow, explosion-like seismic signals were recorded, at least 6 of which were accompanied by confirmed explosions that ejected blocks and produced ash clouds. Gas to drive these events was inferred to come from a deep magmatic source, likely from crystallization of magma in the conduit (Mastin, 1994).

Several other months-long periods of increased deep seismicity occurred after 1992; the most persistent and energetic was in summer 1998. A detectable efflux of CO_2 during this 1998 seismicity (Gerlach and others, this volume, chap. 26) suggested that magmatic intrusion was involved. Although scientists infer that some intrusion happened between 1987 and 2004 (Moran and others, this volume, chap. 2), geodetic surveys offer no support for a substantial increase in volume or pressure in the magmatic system after about 1990 (this volume: Dzurisin and others, chap. 14; Lisowski and others, chap. 15; Poland and Lu, chap. 18).

Throughout 1986–2004, winter snowfall and avalanche snow, alternating with summer rockfall debris from the crater walls, was accumulating in the moat between the 1980–86 lava dome and crater wall. By 1996 the mass was thick enough to initiate glacier flow and to form steep advancing snouts at a time when most of Earth's glaciers were shrinking (Schilling and others, 2004). As the volcano reawakened in 2004, the glacier, formally named Crater Glacier in 2006, formed a collar around three sides of the dome and was gaining mass yearly. South of the dome, the glacier's surface stood as much as 150 m above the 1986 crater floor.

During this time of relative quiescence, media attention to periods of increased seismicity and to anniversaries of the 1980 eruption, as well as other Mount St. Helens' issues, kept the volcano in the news and maintained awareness among the public that the volcano was active and could erupt again. Attention was periodically focused on the volcano as a result of policy discussions related to continuing high sediment production in the Toutle River basin (Major and others, 2000), to longevity and effectiveness of the sediment-retention structure built on the North Fork Toutle River, to the environmental impact of a proposed extension of State Route 504 across the Pumice Plain north of the crater, and to concerns regarding long-term funding issues at the Monument. Educational programs at the Monument and in local school districts also helped to maintain awareness of potential hazards.

Chronology of Events: 2004 to Early 2006

Beginning on September 23, 2004, three weeks of intense seismicity, punctuated by four brief explosions along with localized intense ground deformation, signaled a vent-clearing phase. During this phase there was great uncertainty as to how the unrest would progress and what style of eruption would likely result. The final week of vent clearing was characterized by lessened seismicity, but continued localized intense ground deformation. A phase of continuous lava-dome building, which is subdivided further by Vallance and others (this volume, chap. 9), began on October 11, 2004, and continues at the time of this writing (spring 2006). The highlights of each phase are summarized below, taken largely from contributions in this volume.

Vent Clearing—September 23 to October 5, 2004

A two-day swarm of tiny (mostly M_d<1), shallow volcano-tectonic earthquakes beginning early on September 23, 2004, resembled a swarm in November 2001 (Moran and others, this volume, chap. 2) and prompted release of an Information Statement by USGS–CVO and PNSN at 1800 PDT on September 23 (table 1, fig. 2). The statement discussed the swarm's similarity to previous ones and surmised that this swarm might reflect heavier-than-normal precipitation in the preceding four weeks. A rain gage at the mouth of the Mount St. Helens crater had recorded an abnormally wet last month of summer—more than 30 cm of rainfall. An update on the morning of September 24 noted the difference between the shallow seismicity of the past day and activity during summer 1998 that consisted of larger and deeper events and was considered evidence of deep magmatic intrusion. Both statements considered eruption unlikely without significant further precursors.

Beginning on the afternoon of Saturday, September 25, earthquakes increased in magnitude (M_d ≤2.8), and by the following morning a total of ten M_d >2.0 earthquakes had

Table 1. Systems used by U.S. Geological Survey–Cascades Volcano Observatory for event notification at Mount St. Helens during 2004–2006 eruption for hazards on the ground and for ash hazard to aircraft in flight.

[Terms in use when eruption began. On October 1, 2006, all U.S. Geological Survey volcano observatories adopted a new notification system for volcano hazards that uses some different terms and changes definitions of some levels. See http://volcanoes.usgs.gov/2006/warnschemes.html or http://pubs.usgs.gov/fs/2006/3139/ for details.]

Notification for Ground Hazard	
Information Statement	Describes short-lived events that may or may not be hazardous or gives commentary on status of volcano. May also be issued to provide commentary about notable events occurring within any staged alert level during volcanic unrest.
Staged alert levels	
1 Notice of Volcanic Unrest	First recognition of conditions that could lead to a hazardous event
2 Volcano Advisory	Hazardous volcanic event likely but not expected immediately, or ongoing eruption with localized hazards[1]
3 Volcano Alert	Hazardous volcanic event underway or expected within a few hours or days
Notification of Ash Hazards to Aircraft	
Aviation Color Code	
Green	Volcano is quiet; no eruption is anticipated
Yellow	Volcano is restless; eruption is possible but not known to be imminent
Orange	Small explosive eruption(s) either imminent or occurring; ash plume(s) not expected to reach 25,000 feet above sea level
Red	Major explosive eruption imminent or occurring; large ash plumes expected to reach at least 25,000 feet above sea level

[1] The second part of the definition was added during the current eruption.

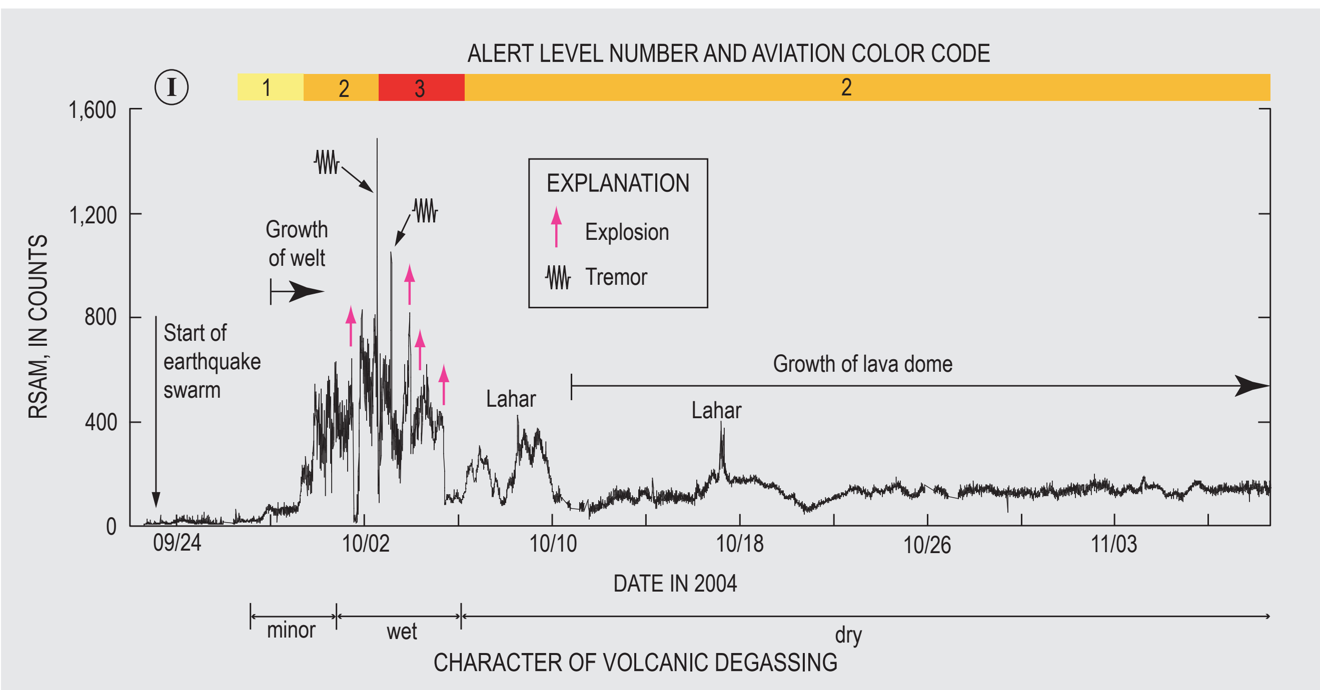

Figure 2. Real-time seismic amplitude measurement (RSAM) during first 6 weeks of unrest and eruption at Mount St. Helens served as proxy for rate of seismicity (modified from Moran and others, this volume, chap. 2). Times of explosions and periods of tremor are shown by symbols. Character of degassing from Dzurisin and others (2005). For meaning of numerals and colored bars indicating alert levels and aviation color codes, see table 1; I, release of first information statement.

been recorded—the most in a 24-hr period since lava-dome building ended in 1986. This increase in seismicity, along with the appearance of low-frequency and hybrid earthquakes, prompted reassessment of the probability of hazardous activity (Moran and others, this volume, chap. 2). At 1500 PDT on Sunday, September 26, after notifying the Washington State Emergency Management Division and GPNF, USGS–CVO and PNSN released a Notice of Volcanic Unrest (table 1; fig. 2), indicating that seismicity had surpassed background level and that the volcano was in a state that could evolve toward eruption. Greatest concern was for explosions such as those between 1989 and 1991 that could shower the crater and upper flanks with ballistic fragments and create ash clouds that could affect aircraft in flight and downwind communities.

The increase in alert level spurred several actions. The GPNF activated their Emergency Coordination Center and closed the south-flank climbers' trail and other trails near the crater (Frenzen and Matarrese, this volume, chap. 23). The number of daily media inquiries, chiefly to USGS–CVO, PNSN, and the Monument, rose rapidly, requiring a considerable effort to be directed toward interviews and briefings (Driedger and others, this volume, chap. 24). High rates of both seismicity and public interest in earthquake information compelled PNSN to develop new visualization tools for tracking seismicity and to establish independent Web sites for the public and for sharing information with USGS–CVO and other scientific partners (Qamar and others, this volume, chap. 3).

Field crews took advantage of uncommonly clear autumn weather to begin installation of additional seismometers and global positioning system (GPS) receivers around the volcano. Fortunately, Earthscope's Plate Boundary Observatory had been planning installation of a network of continuous GPS instruments at Mount St. Helens, and they were able to accelerate their program. Aerial observations of the crater at this time showed no obvious changes, but, in retrospect, a series of new cracks had appeared in the glacier immediately south of the 1980–86 lava dome between September 25 and 26. An uplifted area coincident with the cracks was confirmed by USGS observers on September 29 (Dzurisin and others, this volume, chap. 14).

By September 29 seismicity had intensified to about three events per minute with maximum magnitudes of M_d 2.4–2.8, rising RSAM (real-time seismic amplitude measurement) values (Moran and others, this volume, chap 2), and hours-long periods during which repetitive earthquakes of similar waveform dominated the records (Thelen and others, this volume, chap. 4). The well-known association of such seismicity with lava-dome-building eruptions of the past few decades at Mount St. Helens and elsewhere raised eruption concerns further and prompted issuance of a Volcano Advisory (table 1, fig. 2) midmorning on September 29. The aviation color code (see table 1) was raised to Orange because of increasing concern that explosions could send ash to altitudes where air traffic would be affected. The Volcano Advisory signified that processes were underway that could lead to hazardous eruptive events, but not imminently. Initial airborne missions to detect volcanic gases (carbon dioxide, sulfur dioxide, and hydrogen sulfide) found little, if any (Gerlach and others, this volume, chap. 26). Interpretation of the apparent lack of volcanic gas was tempered by the possibility that such gas had been scrubbed at the high water-to-gas mass ratios likely to be present at shallow levels beneath the nearly glacier-covered crater floor.

The alert-level rise to Advisory triggered the GPNF to activate a local Incident Management Team and to begin discussions with other agencies regarding a Joint Operation Center, which would be necessary if unrest continued to escalate or eruptions began (Frenzen and Matarrese, this volume, chap. 23). Intense media interest, directed chiefly toward USGS–CVO and the Monument, was beginning to adversely affect operations, so local and State emergency management agencies joined with USGS–CVO and the GPNF to begin organizing a Joint Information Center (Driedger and others, this volume, chap. 24).

Real-time seismic amplitude values increased again on the evening of September 29, reflecting an increase in maximum earthquake magnitudes (M_d 2.8–3.3) and rate of earthquakes of M_d>2 to about 1 per minute. The RSAM values fluctuated over the next 1.5 days. Flights during this time period again failed to detect significant amounts of volcanic gas. However, the uplifted and cracked area of the glacier south of the 1980–86 lava dome, along with a sliver of the dome, was continuing to fracture and rise several meters per day, creating what became known as the welt (Vallance and others, this volume, chap. 9; Dzurisin and others, this volume, chap. 14). Data from a GPS receiver on the west side of the 1980s lava dome showed northward movement of several centimeters per day, consistent with a shove from a rising mass south of the dome (LaHusen and others, this volume, chap. 16).

The inaugural flight at Mount St. Helens of a helicopter-mounted forward-looking infrared radiometer (FLIR) midday on October 1 was rewarded with close observation of the first explosion of the current eruption, which bored an ice-walled crater through the western part of the welt (figs. 3*A*, *B*; Schneider and others, this volume, chap. 17). The FLIR recorded a maximum temperature at the base of the explosion column of ~160°C, well below magmatic temperature, which suggested that the explosion was driven largely by steam. The explosion was also witnessed by several thousand cheering visitors at the Monument and became clearly visible from the Portland metropolitan area, 80 km southwest, as an ash and vapor cloud rose about 2 km above the crater rim and drifted southwestward. Neither this nor other explosions over the next few days had any recognizable precursors (Moran and others, this volume, chap. 6). Earthquakes stopped about 1 minute after the explosion started, and when the explosion signal also ended abruptly 19 minutes later, helicorders were quiet for about 3 hours. The rate of earthquakes rapidly increased again during the evening, and by late evening RSAM values exceeded those prior to the explosion, suggesting that the explosion had relieved elevated pressure in the conduit but that the system was repressurizing quickly (Moran and others, this volume, chap. 2).

For the next two days (October 2–3), seismicity remained at a high level of several thousand events per day, punctuated by earthquakes of M_d 3.5–3.9. Midday on October 2, a 50-minute episode of energetic, relatively broadband seismic tremor (Moran and others, this volume, chap. 2), coupled with hints of volcanic gas during the previous few days (Gerlach and others, this volume, chap. 26) and a continued high rate of growth of the welt, prompted USGS–CVO and PNSN to issue a Volcano Alert at 1400 PDT (table 1, fig. 2). Because of concern over an imminent and potentially hazardous event, the GPNF evacuated the Johnston Ridge Observatory (JRO), 8 km north of the crater, the Washington State Department of Transportation closed State Route 504 at the Coldwater Ridge Visitor Center, and land and air space was closed within 8 km (5 mi) of the crater (Frenzen and Matarrese, this volume, chap. 23). A key concern was that an explosive magmatic eruption could produce pyroclastic flows, swiftly melt large amounts of snow and ice surrounding the vent, and generate lahars that could sweep into the upper North Fork Toutle River valley. The increased possibility of ash clouds reaching high altitudes where they could affect air traffic warranted raising the aviation color code to Red.

Memories of the catastrophic events of May 18, 1980, preoccupied many media and citizens, so a major public-information effort was required to maintain a realistic hazard perspective (Driedger and others, this volume, chap. 24). An explanation that seemed to reduce anxiety was that the 1980 eruption had so eviscerated Mount St. Helens, creating a deep crater open to the north, that the volcano could no longer support a scenario of intrusion of a cryptodome, large flank failure, and catastrophic lateral blast. Consensus among scientists at USGS–CVO and PNSN was converging on two possible scenarios for volcanic activity over the coming weeks to months. These were transmitted to land and emergency managers. One focused on resumption of lava-dome growth accompanied by explosive events of volcanic explosivity index (VEI) 2–3. The other included the possibility of eruptions of VEI 4 to low 5, similar to the hours-long plinian eruption on the late morning and afternoon of May 18, 1980.

Interest on the part of the media and the public peaked during the first few days of October, resulting in high rates of inquiry and visits to Web sites (Driedger and others, this volume, chap. 24). A Joint Information Center opened on October 3, and a Joint Operations Center under unified command

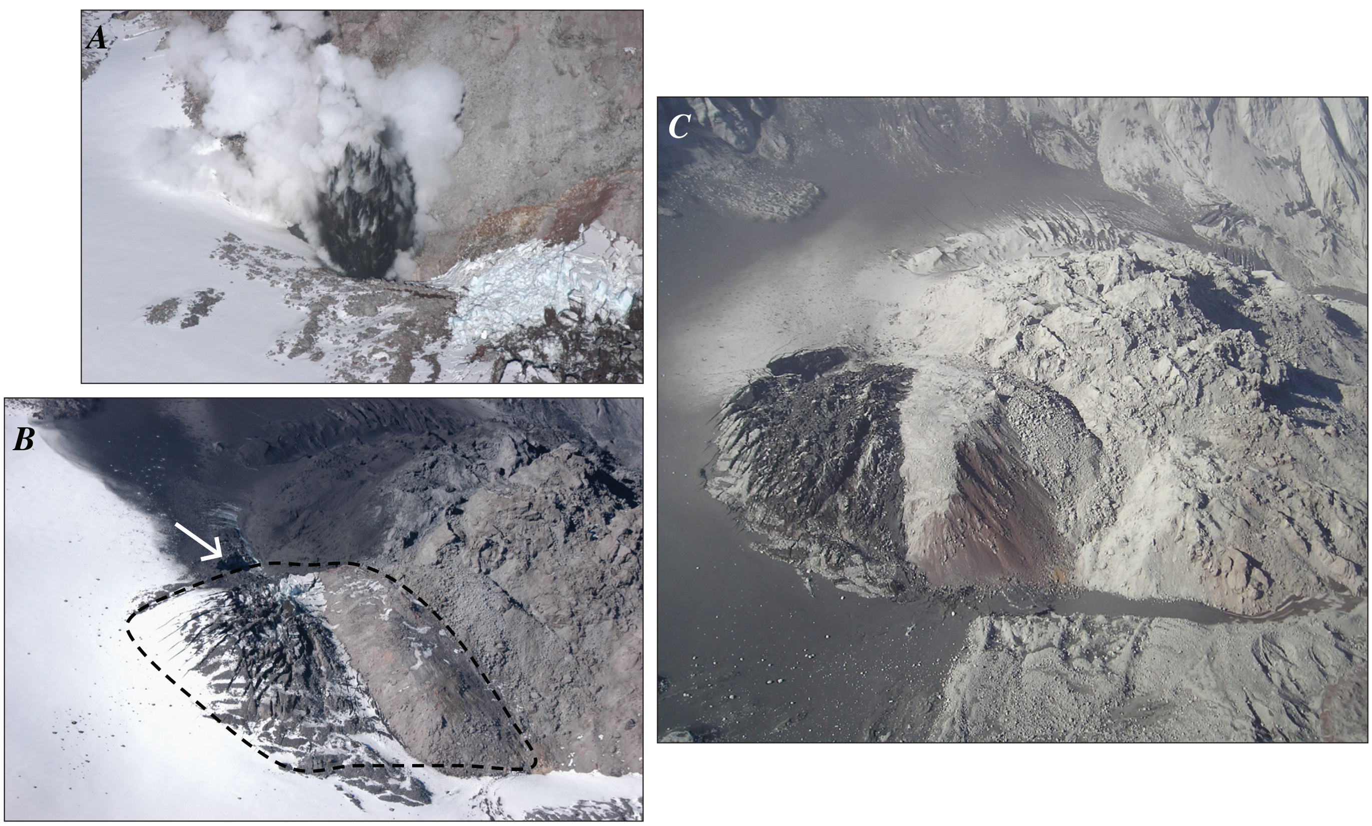

Figure 3. Crater features seen during first two weeks of the eruption of Mount St. Helens. *A*, Start of explosion of October 1, 2004, looking north across glacier toward 1980–86 lava dome. USGS photograph by J.S. Pallister. *B*, Looking west about 30 minutes after explosion of October 1, 2004, ended. USGS photograph by J.S. Pallister. Note tephra-covered snow and crater (white arrow) bored at west end of welt (dashed line), which is formed of uplifted glacier ice and southern part of 1980–86 lava dome. *C*, Noticeably larger welt on October 4, 2004, looking west. Some tephra of October 1 and 4 explosions is drying to light color. USGS photograph by S.P. Schilling.

was established the following day with representatives from key land-management and emergency-management agencies (Frenzen and Matarrese, this volume, chap. 23).

Additional explosions late on October 3 and midmorning on October 4 were followed by decreases and rebounds in seismicity much less dramatic than those on October 1; the last explosion on October 5 initiated a drop in RSAM that has never recovered (fig. 2; Moran and others, this volume, chap. 2). This last explosion, rating a VEI of 2, was the most vigorous, generating an ash plume that reached about 2 km above the crater rim. The plume drifted to the north-northeast, lightly dusting several communities and the eastern part of Mount Rainier National Park, about 100 km away.

The relatively low level of seismicity that followed the October 5 explosion, including multiplets of hybrid events with similar wave forms (Thelen and others, this volume, chap. 4), combined with moderate gas emissions (Gerlach and others, this volume, chap. 26) and continued growth of the welt (fig. 3*C*; Dzurisin and others, this volume, chap. 14), suggested that the eruption would probably progress to lava-dome extrusion. Under such conditions, the probability of hazardous events affecting areas beyond closures was small, except for ash clouds that could pose hazards to aircraft. Therefore, at 0915 PDT on October 6, USGS–CVO and PNSN lowered the alert level to Volcano Advisory, where it has remained since (table 1, fig. 2). Concurrently, the aviation color code was lowered to Orange. The GPNF reverted to a local Incident Management Team (Frenzen and Matarrese, this volume, chap. 23), and inquiries to the Joint Information Center began to decline, eventually leading to its being disbanded on October 13 (Driedger and others, this volume, chap. 24). USGS–CVO continued to update agencies through daily conference calls.

Vent Clearing—Waiting for Lava—October 5 to October 11, 2004

Several days of stormy weather beginning on October 6 drove visitors and media from the Monument, increased RSAM with storm noise, and generated a small lahar from the crater—a common occurrence with the onset of autumn rain. Brief views through the clouds showed that the welt continued to grow upward and outward, reaching more than 100 m above the former glacier surface. On October 10 a fixed camera on Sugar Bowl dome, at the northeast mouth of the crater, began transmitting images that tracked growth of part of the welt (Poland and others, this volume, chap. 11). Later analysis of digital elevation models (DEMs) showed that by October 11 the deformed area had a volume of about 10×10^6 m^3 (Schilling and others, this volume, chap. 8). FLIR measurements confirmed that by October 10 an area on the northwest part of the welt had reached temperatures >270°C, suggesting that the crater floor was being heated and pushed upward by rising magma (Schneider and others, this volume, chap. 17). An airborne survey on October 7 measured gas-emission rates of ~2,400 metric tons per day (t/d) CO_2, ~100 t/d SO_2, and ~10 t/d H_2S, which, although relatively modest for volcanoes such as Mount St. Helens, suggested that a dry pathway had been established and scrubbing of SO_2 reduced (Gerlach and others, this volume, chap. 26). The question on everyone's mind and asked repeatedly by the media was, "Has new lava appeared on the surface yet?"

Lava-Dome Growth—October 11, 2004, to Spring 2006

On October 11, a FLIR survey revealed a newly extruded fin-shaped rock spine (in retrospect designated spine 1) about 30 m high and 60 m long and having a maximum temperature of about 580°C (Schneider and others, this volume, chap. 17); this spine is considered to have been the initial appearance of new lava (fig. 4) and the start of growth of what we call the new lava dome (this volume: Schilling and others, chap. 8; Vallance and others, chap. 9; Herriott and others, chap. 10). The spine occupied the approximate location of the vent for early October explosions and stood >200 m above the crater floor. In the following days the spine grew, its base and cracks showed temperatures as high as 700°C, and additional areas of hot rock appeared to the south of spine 1 (designated spine 2; Vallance and others, this volume, chap. 9). The first samples of the new lava dome were dredged from spine 1 on October 20 using a weighted bucket on the end of a 30-m line slung from a helicopter. The samples looked like typical Mount St. Helens dacite (Pallister and others, this volume, chap. 30). During mid-October, RSAM fluctuated broadly, multiplets of hybrid earthquakes appeared and faded, and seismicity settled into a pattern of repetitive small (M_d <1) earthquakes, dubbed "drumbeats," occurring at a rate of one to two per minute, with larger events at longer intervals (Moran and others, this volume, chap. 2).

The potential for unpredictable explosions induced decisions to minimize the exposure of field crews; beginning in early October 2004, most new and replacement instruments in the crater were deployed by helicopter sling. Single-frequency GPS receivers and accelerometers (seismometers) mounted alone or together on tripods, dubbed "spiders," proved invaluable for maintaining close-in monitoring by telemetered seismic instruments (McChesney and others, this volume, chap. 7) and for allowing real-time geodetic measurements of rates and directions of movement of the welt and new dome, as well as movement of the glacier and deformation of the old lava dome (LaHusen and others, this volume, chap. 16; Dzurisin and others, this volume, chap. 14; Walder and others, this volume, chap. 13).

Growth of the new lava dome at Mount St. Helens has progressed steadily since mid-October 2004, apparently without pause (this volume: Schilling and others, chap. 8; Vallance and others, chap. 9; Herriott and others, chap 10; Poland and others, chap. 11; Major and others, chap. 12). In contrast, the old (1980–86) lava dome grew in episodic spurts on either side of a one-year period of continuous growth (Swanson and Holcomb, 1990). Rather than building a single dome-shaped structure similar to the old dome, the new dome grew initially as a series of recumbent, smoothly surfaced spines or "whalebacks" that extruded to lengths of almost 500 m. As is typical for such spines (Williams, 1932), their surfaces were striated and grooved and formed of powdery, crushed rock (gouge) and cataclasite that result from the solid extrusion grinding against the conduit walls during its last few hundred meters of ascent (Cashman and others, this volume, chap. 19; Moore and others, this volume, chap. 20). The gouge on early spines contained both dacite from the extrusion and more mafic constituents interpreted to have come from the conduit walls, but during most of the eruption, gouge has been formed entirely of dome dacite (Rowe and others, this volume, chap. 29; Pallister and others, this volume, chap. 30).

The dacite building the new dome is similar in chemical composition (~65 weight percent SiO_2) and mineralogy (plagioclase>hornblende≈hypersthene) to the dacite erupted on May 18, 1980, and is among the most silica-rich and incompatible-element-depleted magmas of the past 500 years at Mount St. Helens (Pallister and others, this volume, chap. 30). The dome lava contains 40–50 percent phenocrysts, and the groundmass is largely crystalline for most of its last 500 m of ascent (Cashman and others, this volume, chap. 19). In several contributions in this volume, petrologists and geochemists explore evidence for the origin of the lava and its recent history. Some of it is thought to represent residual magma from the 1980s, but several lines of evidence suggest that a component of a different dacite is mixed with the 1980s dacite—one newly arrived in the magma chamber or one from a part of the magma chamber that was not tapped in the 1980s (this volume: Pallister and others, chap. 30; Thornber and others, chap. 32; Blundy and others, chap. 33; Streck and others, chap. 34; Kent and others, chap. 35; Cooper and Donnelly, chap. 36; Reagan and others, chap. 37). Thin reaction rims on amphibole phenocrysts suggest storage for a prolonged period at depths of 4–5 km or deeper, followed by rapid ascent through the conduit (Rutherford and Devine, this volume, chap. 31).

Late Autumn 2004

The first of the whaleback-shaped spines (spine 3) started growing in late October 2004 from a spot just southeast of spine 1 and east of spine 2. A GPS spider riding on the spine moved at an average rate of about 10 m/d for 8 days (LaHusen

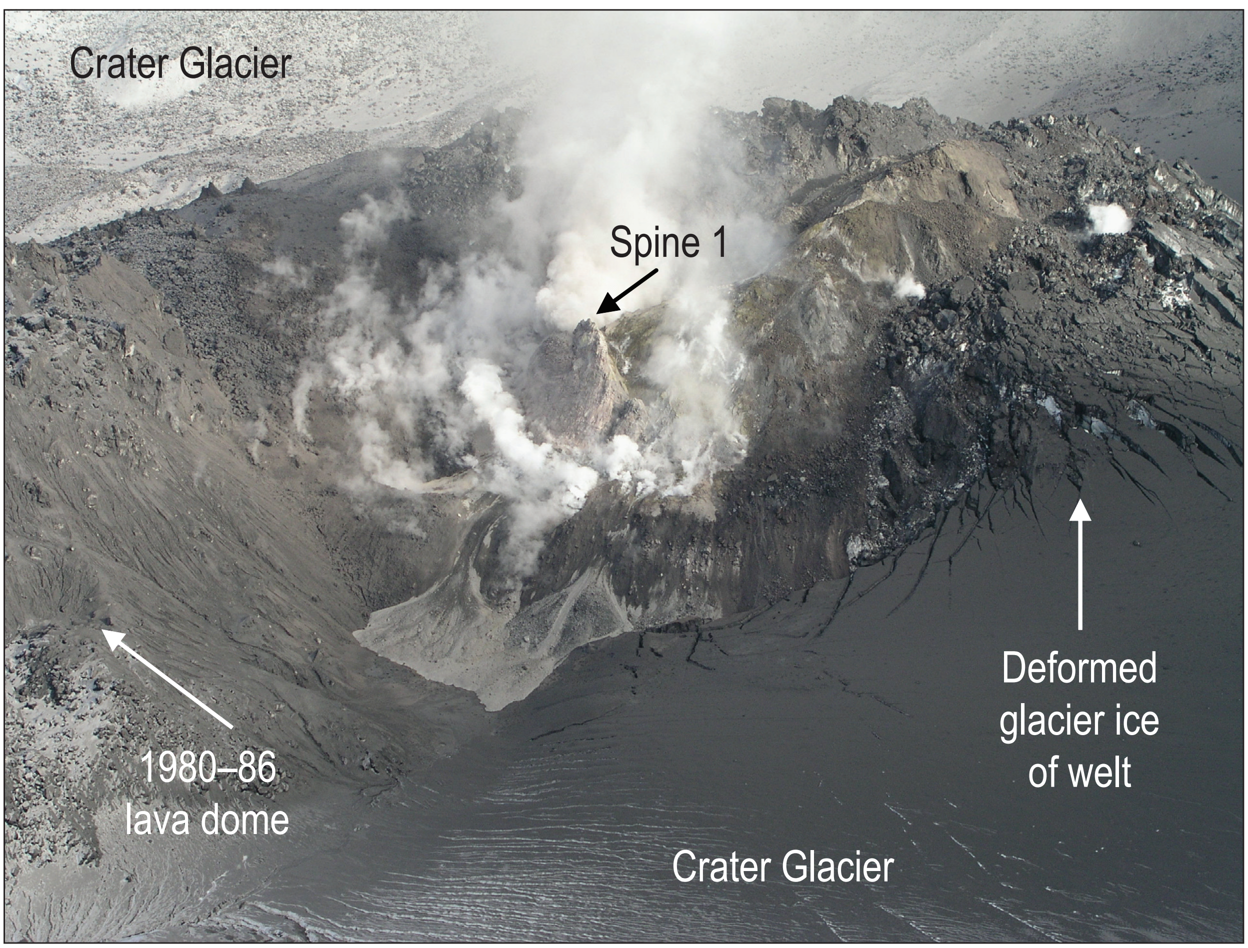

Figure 4. First view (toward southeast) of hot, new lava at surface in crater of Mount St. Helens, October 11, 2004. Spine 1 is composed of pinkish-gray dacite that is disintegrating and forming light-colored debris fans between welt, old dome, and west arm of glacier. USGS photograph by J.J. Major.

and others; this volume, chap. 16). By the end of November 2004, spine 3 was about 475 m long and had reached the base of the southeast crater wall; by mid-December, the total volume increase represented by the three spines of the new dome and welt, using the 1986 crater floor as a base datum, was about 30×10^6 m^3 (Schilling and others, this volume, chap. 8). Whether because of the increasing difficulty of extruding an ever-lengthening mass or because of stress imposed by impinging on the crater wall, longitudinal fractures appeared and widened and transverse fractures severed the spine from the vent in mid- to late December (fig. 5). The breakup of the spine was accompanied by sporadic earthquakes of M_d ~2.5–3.5, suggesting a causal relation (Moran and others, this volume, chap. 2). The remaining stump of spine 3 grew to form a new spine (spine 4) that pushed most of the old spine 3 aside to the east, except for a small amount that was stranded on the west side of spine 4 (Vallance and others, this volume, chap. 9; Herriott and others, this volume, chap. 10). As spine 3 was pushed eastward, it became increasingly fractured, and little of its original smooth, gouge-covered surface remained intact.

January to July 2005

Growth and disintegration of spines continued through the first 8 months of 2005. Spine 4 formed a prominent whaleback whose growth ended similarly to that of spine 3, whereas spine 5 grew at a steeper angle and its south end trended more southwesterly than did spines 3 and 4 (Vallance and others, this volume, chap. 9). Growth periods of spines 4 and 5 each lasted about 13 to 14 weeks. Extrusion rates during the growth of spines 4 and 5 were lower than during growth of spine 3 (Schilling and others, this volume, chap. 8), as were linear rates of motion measured by GPS spiders (LaHusen and others, this volume, chap. 16), by analysis of repeat photographs from the crater mouth (Major and others, this volume, chap. 12), and by tracking of points through sequential DEMs (Vallance and others, this volume, chap. 9). By midsummer 2005, the top of spine 5 reached the highest altitude attained by the new dome, 2,368 m. At that time the top stood only a few meters below the lowest point on the crater rim, Shoestring notch, and about 180 m below the present summit of Mount St. Helens; the dome then towered about 450 m above the 1986 crater floor. Spine 5 was a prominent feature in the view of the crater from JRO in midsummer 2005, with the crumbled remains of spine 4 and its large raft of intact gouge-covered surface lying off to the east (fig. 6*A*).

August 2005 to Spring 2006

A key change in the pattern of dome growth began in late July 2005, as towering spine 5 began to crumble rapidly. Rather than follow the previous pattern of a new spine growing southward and bulldozing the remains of older spines chiefly eastward, the growth of spine 6 progressed westward. The likeliest explanation is that spine 6 faced less resistance by plowing into the west arm of the glacier than by continuing to push into the previously extruded dome (Vallance and others, this volume, chap. 9). Although spine 6 had some areas displaying the smooth, gouge-covered surface typical of earlier whalebacks, it formed a more domical mass than had previous spines. Photogrammetric techniques estimated a rate of movement of several meters per day westward and upward (this volume: Major and others, chap. 12; Dzurizin and others, chap. 14). As spine 6 moved westward, the west side of spine 5, which was by then highly fractured, slumped westward into a widening sag forming between the two spines.

By mid-October 2005, a new spine was detected in FLIR imagery to be rising between spines 5 and 6 (Vallance and others, this volume, chap. 9). Spine 7 rode up the east side of spine 6, and both continued to move westward (fig.

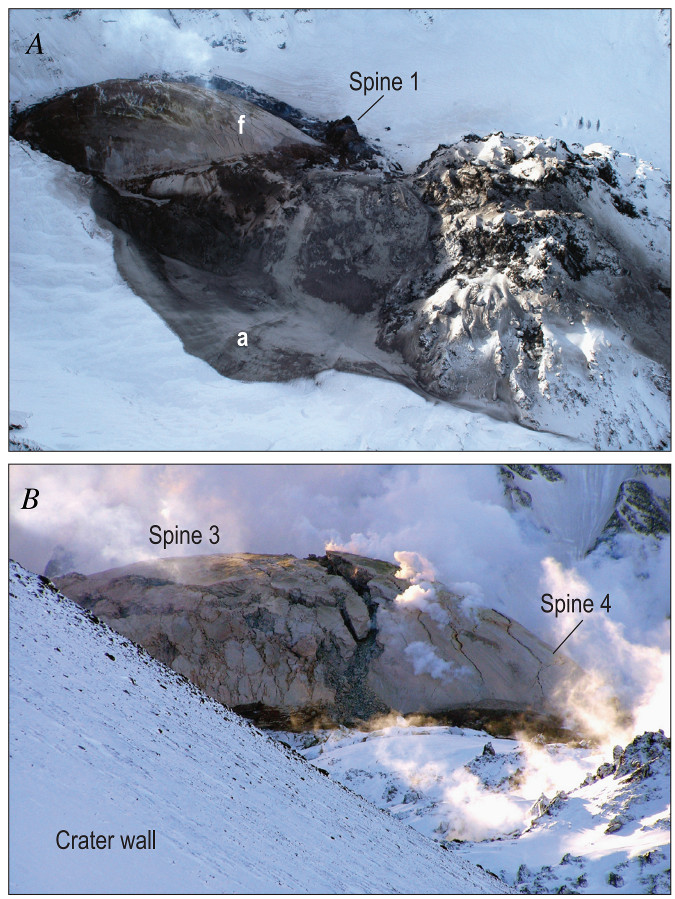

Figure 5. Views of spine 3. *A*, On December 16, 2004, spine was at its maximum extent just as fractures (f, right of the white vapor plume) were beginning to develop that would eventually sever the spine from the vent; view to west. Note thin deposit of ash formed by density current(s) of ash (a) originating as slough(s) of fine-grained gouge carapace. USGS photograph by W.E. Scott. *B*, One week later, fractures had expanded and severed spine 3 from vent; spine 4 was riding up on and pushing the disintegrating remains of spine 3 chiefly southeastward; view to southwest. USGS photograph by M.P. Poland.

6*B*). By spring 2006, much of spine 6 had been covered by spine 7 or by an apron of rockfall debris being shed westward from it. The combined mass of spines 6 and 7 continued to move west-northwestward and slightly downward at about 1 m/d during spring 2006 (LaHusen and others, this volume, chap. 16). Even though spines have formed and crumbled repeatedly throughout the eruption, the vent area (the area at which the extrusion breaches the ground surface) has remained in the same approximate position of the early October 2004 explosion pit and initial spine (this volume: Schilling and others, chap. 8; Vallance and others, chap. 9; Herriott and others, chap. 10).

Modest rates of gas emission during initial stages of dome growth in late 2004 diminished to lower rates throughout most of 2005 and early 2006. Typical daily average rates were a few hundred metric tons of CO_2 and a few tens of metric tons of SO_2 (Gerlach and others, this volume, chap. 26). In addition, during late August 2005, a survey from the crater rim using open-path Fourier-transform infrared spectroscopy yielded the first direct measurements of HCl in the plume at Mount St. Helens. The average daily emission rate of HCl was about 60 percent that of SO_2 (Edmonds and others, this volume, chap. 27). Intriguingly, studies of crater-floor and flank thermal and cold springs have shown no effect from the current eruption on either the content of dissolved magmatic volatiles or the temperatures of ground water (Bergfeld and others, this volume, chap. 25).

The future of dome growth at Mount St. Helens remains uncertain. By the end of 2005, the new dome had a total volume of about 73×10^6 m^3, nearly equaling the volume of the old lava dome in a time span about one-fifth as long (fig. 7). The rate of extrusion had declined from about 5 m^3/s in late 2004 to less than 1 m^3/s at the end of 2005. Overall, the rate of extrusion appeared to be either slowing exponentially or becoming relatively linear and fluctuating between <1 and 2 m^3/s (this volume: Schilling and others, chap. 8; Mastin and others, chap. 22). Will the eruption come slowly to a halt over the coming months or years, or will it stabilize at a steady long-term rate? Alternatively, will the rate of extrusion become variable and episodic—more reminiscent of dome growth during the 1980s? Textural similarity of current lava to that of the pre-1980 summit lava dome, which is known to have been emplaced over about 150 years during the 17th and 18th centuries, suggests that the current eruption may last for many more years (Pallister and others, 1992; Pallister and others, this volume, chap. 30). Finally, appreciating the varied eruptive history of Mount St. Helens

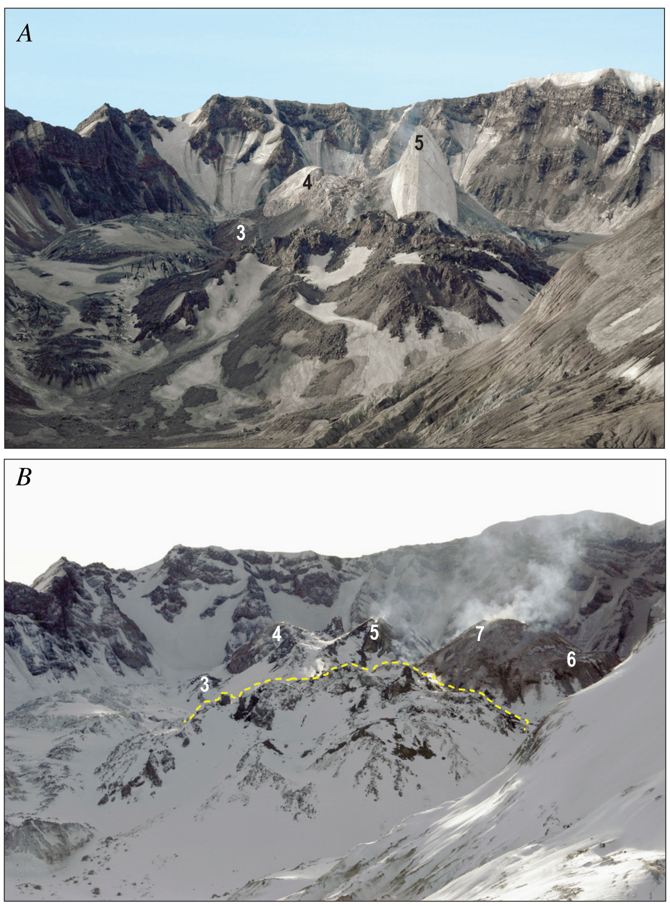

Figure 6. Views south to lava dome in Mount St. Helens' crater from fixed camera point at Johnston Ridge Observatory, 9 km to the north. Numerals denote spines of new lava dome. USGS photographs by E.T. Endo. *A*, June 24, 2005; actively extruding spine 5 is approaching its highest altitude. Note highly crevassed east (left) arm of Crater Glacier, which had been compressed by eastwardly migrating lava dome. *B*, December 5, 2005; spine 5 has disintegrated, and spines 6 and 7 are migrating westward (to right). Yellow dashed line marks profile of 1980s lava dome.

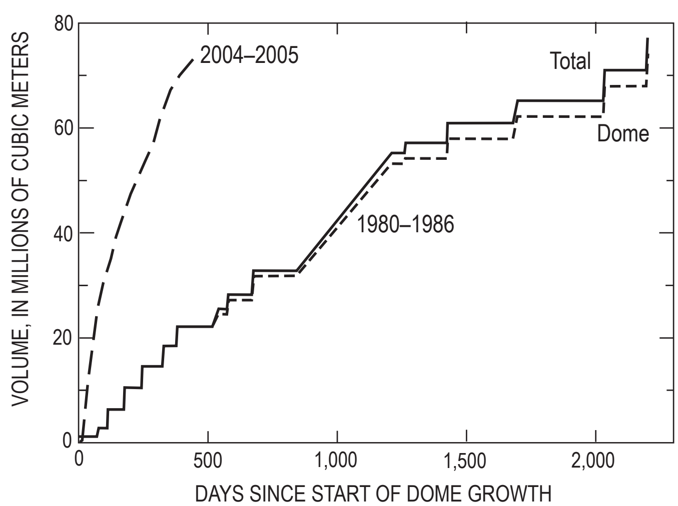

Figure 7. Comparison of cumulative extruded lava volumes for domes of 1980–86 (Swanson and Holcomb, 1990) and 2004–5 (Schilling and others, this volume, chap. 8) at Mount St. Helens. Total for 1980–86 includes tephra and rockfall debris from growing dome.

(Hoblitt and others, 1980), does the volcano have something entirely different in store?

Other Events Related to Dome Growth

Small Explosions Accompany Dome Growth

An explosion early on the stormy morning of January 16, 2005, was the first of two notable explosions during that year. There were no recognizable precursors to the explosion, but any subtle seismic precursors would probably have been lost in storm noise. Transmission from several crater instruments stopped for seconds-long intervals during the explosion's seismic signal, presumably as a result of ash in the air blocking radio signals (Moran and others, this volume, chap. 6). Reception from one near-vent seismometer stopped for several hours. Several other instruments on and close to the actively growing part of the lava dome were destroyed. Poor weather precluded field observations for several days, but a reconnaissance flight eventually revealed evidence of the explosion. Craters from ballistic blocks pockmarked the glacier surface, chiefly east of the new dome, for hundreds of meters. Ash covered the crater east and west of the new dome and formed a narrow deposit on the outer east flank of the volcano, consistent with strong westerly winds. About 5 mm of ash fell on the lower east flank; the extent of ashfall farther east is unknown because of a lack of snow-covered surface to preserve the ash and the heavy rainfall that accompanied and followed the explosion. Effects of the explosion were similar to those of the October 2004 events, but no visible vent crater was formed. A shallow trough along the northeast margin of spine 4 may have marked the vent. The similarity in texture and composition of the ash with previously collected samples of that spine's surficial gouge suggested that the explosion vented along the margin of the spine, entraining powdery gouge and blocks (Rowe and others, this volume, chap. 29).

The second explosion occurred under good viewing conditions late on the afternoon of March 8, 2005 (fig. 8*A*). Seismicity had increased slightly for several hours before the explosion and had initiated a close watch in the operations room at USGS–CVO, but it was not recognized as a precursor to an imminent explosion (Moran and others, this volume, chap. 6). The Sugar Bowl camera at the northeast mouth of the crater captured images of a dense ash cloud rising from near the new dome (Moran and others, this volume, chap. 6, fig. 10) and ballistic-impact craters in snow on the north flank of the old dome. Ballistic fragments destroyed one seismometer located between the old and new lava domes and one seismometer and two microphones located on the old lava

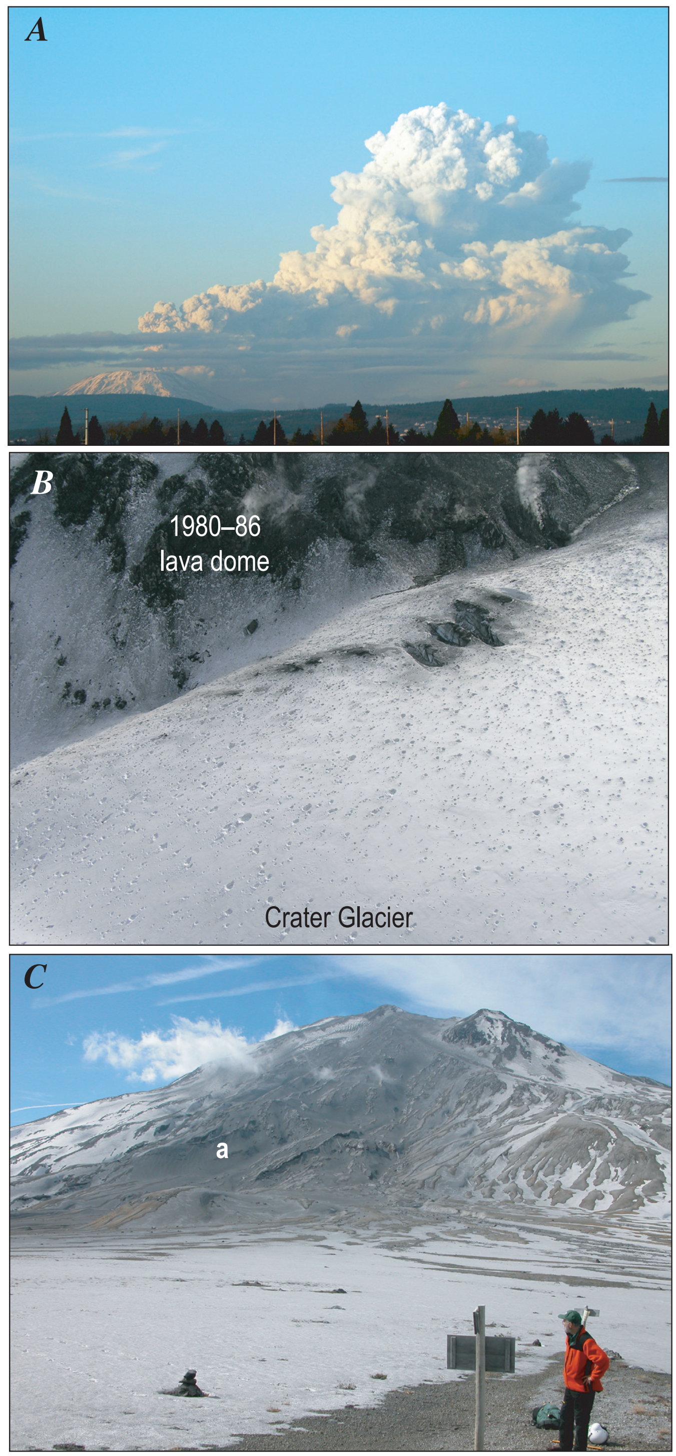

Figure 8. Explosion of March 8, 2005, at Mount St. Helens. *A*, Ash and vapor cloud as viewed toward north-northeast from Cascades Volcano Observatory, 70 km away. USGS photograph by M. Logan. *B*, View to southeast showing northwest base of 1980–86 lava dome and west arm of Crater Glacier pockmarked by craters (as large as 2 m across) formed by rain of ballistic fragments. USGS photograph by D. Dzurisin. *C*, Tephra deposit (a) on east-northeast flank of the volcano as seen from the Plains of Abraham. USGS photograph by D.R. Sherrod. Note the meager snowpack of the winter of 2004–5. *D*, Map showing extent of ballistic fragments and tephra fall from the explosion.

dome. A white vapor cloud billowed high above the crater rim and drifted east-northeastward. Pilots reported the top of the cloud reached an altitude of 11 km; the National Weather Service's NEXRAD detected it up to 6 km. The whiteness of the upper parts of the cloud suggested that it contained little ash. Application of a new one-dimensional steady-state model for wet volcanic plumes using that day's atmospheric conditions indicates that relatively high humidity may have boosted the plume height several additional kilometers (Mastin, 2007). The explosion continued vigorously for about 10 minutes and then waned over several tens of minutes. Investigations the following day revealed a field of ballistic craters (fig. 8*B*) extending about 1 km north-northwest of a poorly defined and vapor-shrouded possible vent area at the north end of the new lava dome. A narrow deposit of coarse ash and fine lapilli extended east-northeastward, discernible on snow for about 7 km from the vent (figs. 8*C*, 8*D*). This fallout deposit was about 20 mm thick on the crater rim and about 2 mm thick on the lower east flank of the volcano. Dustings of ash were reported in Ellensburg, Yakima, and Toppenish, Washington, as far as 150 km from Mount St. Helens. Lithic lapilli as large as 4 cm fell near the crater rim and fragments as large as 1 cm fell on the lower east flank.

Rockfalls and Rock Avalanches

Rockfalls and rock avalanches have both generated small pyroclastic density currents, with reaches of <1 km, and numerous ash clouds that rose above the crater rim. At most, such clouds only weakly dusted the outer flanks of the volcano and traveled only a short distance downwind. Signals of rockfalls and small rock avalanches were common on seismic records, and such events have been directly observed by scientists during hours-long occupations of sites on the old lava dome and crater rim, as well as during fortuitously timed flights (fig. 9). Many such events have also been recorded by fixed cameras (Poland and others, this volume, chap. 11). The largest avalanches observed have been on the order of tens of thousands of cubic meters, but most have been much smaller. Periods of rapid disintegration of spines and accompanying large earthquakes favored large avalanches and frequent rockfalls. The high degree of crystallinity and low gas content of the lava (this volume: Pallister and others, chap. 30; Gerlach and others, chap. 26; Edmonds and others, chap. 27) are probably responsible for the relatively small amount of ash generated by avalanches and rockfalls and the restricted distribution of deposits of

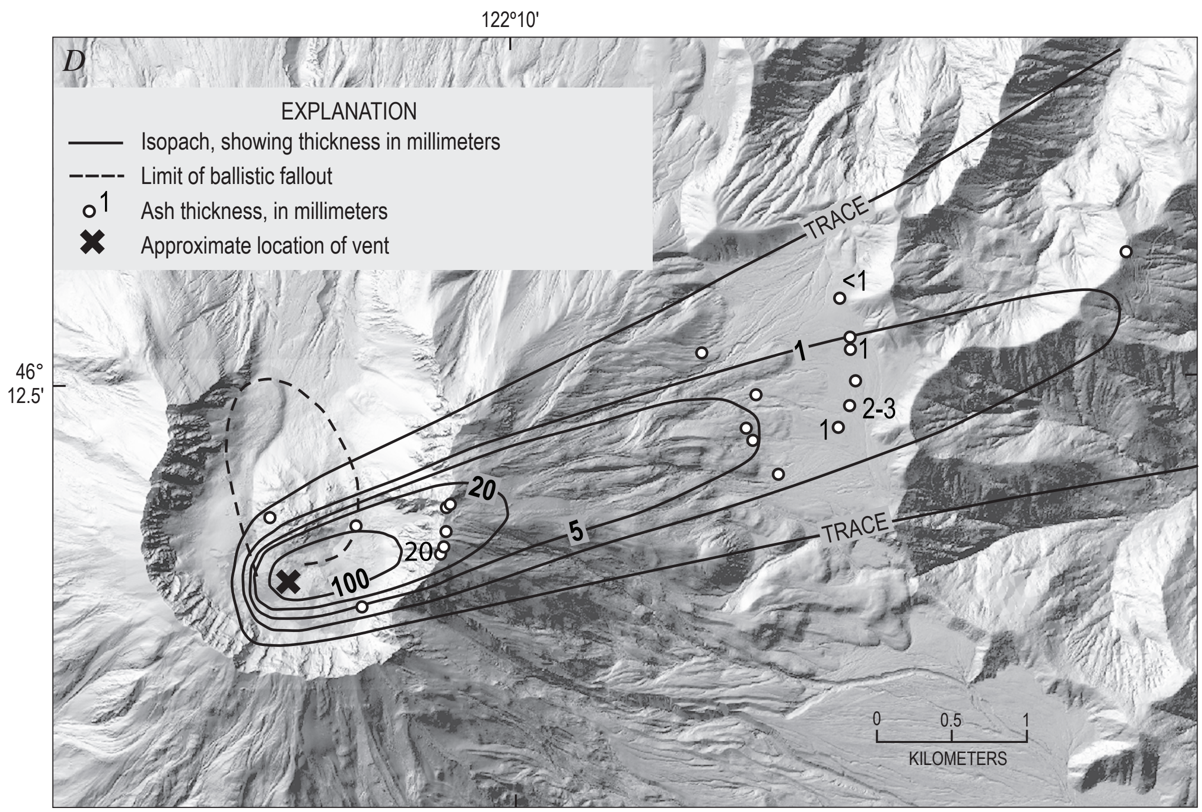

Figure 8—Continued.

resulting density currents. Sloughing of ashy gouge from the outer parts of whaleback-shaped spines, especially spine 3, has also created weak density currents of ash and accompanying ash clouds (fig. 5*A*).

Dome Growth Perturbs Glacier

Continued eastward movement of spines 3, 4, and 5 through late summer 2005 greatly compressed, thickened, and fractured the east arm of Crater Glacier (fig. 6*A*). Such conditions created an unprecedented glaciological experiment (Walder and others, this volume, chap. 13). The resulting doubling of thickness accelerated surface movement to more than 1 m/d, which, although high for such a small glacier, is less than would be expected from such a dramatic thickening. The explanation for lower-than-expected flow rate is that the bed of the glacier, which comprises talus and coarse pyroclastic debris, is so permeable that water pressure at the bed cannot rise sufficiently to induce rapid basal sliding (Walder and others, 2005). In response to this perturbation, the snout of the glacier's east arm thickened noticeably and advanced markedly during winter of 2005.

Beginning in late summer 2005, westward movement of spines 6 and 7 started compressing the west arm of Crater Glacier (fig. 10). As a result, a similar thickening and accelerated flow rate began to occur on the west arm (Walder and others, this volume, chap. 13).

A remarkable aspect of the interaction of the growing lava dome and glacier is the apparent lack of significant glacier melting (Walder and others, 2005; this volume, chap. 13). As the glacier grew in the crater between 1986 and 2004, USGS–CVO noted the potential for increasingly larger lahars if future explosive eruptions or lava-dome collapses generated pyroclastic flows. Such concerns dominated the hazard outlook for the first few weeks of unrest in 2004. Once lava-dome growth commenced, the lahar hazard assessment focused on the possibility of explosions from the dome swiftly melting snow in the crater, as had happened in 1982 and 1984 (Pierson, 1999), as well as on collapses from the new lava dome incorporating and melting snow and ice. Neither scenario has transpired to date (summer 2006). Explosions in January and March 2005 did not generate pyroclastic flows or surges of note and apparently melted little snow and ice. Rockfalls and rock avalanches from the dome have been of modest size, and neither they nor pyroclastic density currents derived from them have induced much melting (fig. 9*B*).

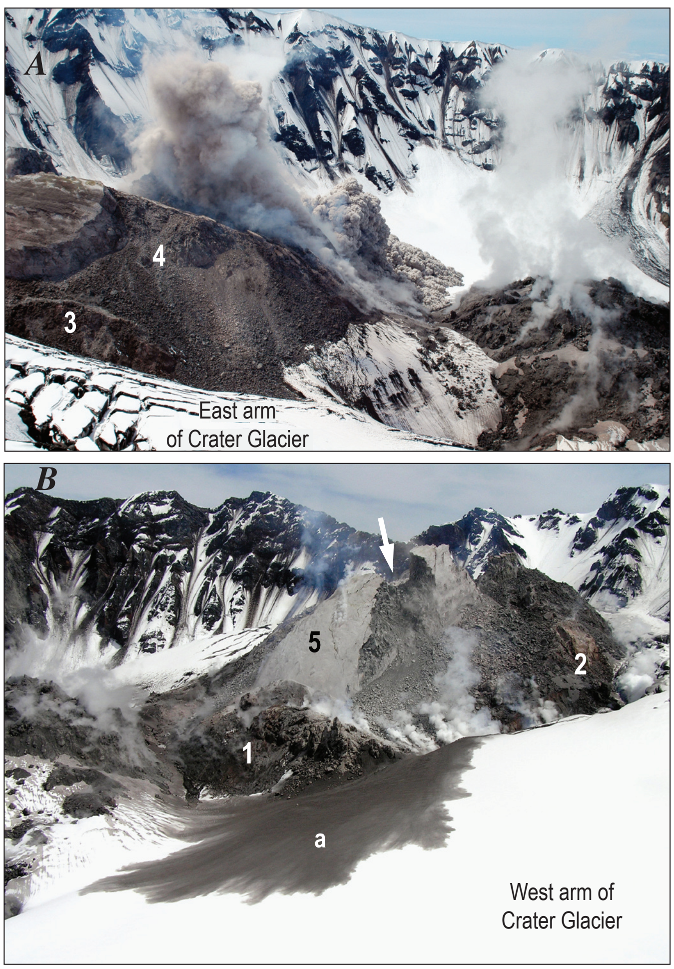

Figure 9. Rock avalanche from spine 5 and associated ash cloud and small pyroclastic density current of May 12, 2005; spine 5 and older spines designated by numerals. *A*, View from east crater rim of density current flowing northwestward and ash cloud rising and obscuring spine 5. USGS photograph by M. Logan. *B*, Aerial view from northwest following event, showing scar at rockfall source (arrow) and thin ash deposit (a) on snow. USGS photograph by D. Dzurisin.

New Insights from the Ongoing Eruption

Mount St. Helens' ongoing extrusion of gas-poor dacitic lava has presented an opportunity to develop and improve a variety of models. These models can illuminate controls on the volcano's eruptive behavior.

Scientists were tantalized by the persistent "drumbeat" earthquakes, at times amazingly periodic, that have accompanied nearly steady lava extrusion since early in the eruption (Moran and others, this volume, chap. 2). Were the drumbeats an indication of repetitive stick-slip motion along the margins of the extruding plug, producing the coating of striated fault gouge? Strength tests of gouge samples support this hypothesis and also show evidence for rate-weakening friction (Moore and others, this volume, chap. 20). A dynamical model demonstrates that repetitive stick-slip events are an almost inevitable consequence of magma influx at a near-equilibrium rate occurring in conjunction with rate-weakening frictional slip along the margins of an extruding solid plug (Iverson and others, 2006; Iverson, this volume, chap. 21). Because such a condition was attained very early in this eruption, the model implies that the magma-plug system was probably close to equilibrium at the onset and perhaps needed only a small perturbation to be triggered into action. It remains unknown whether the trigger was related to a small increase in magmatic pressure, to pressure increase caused by accumulation of an excess-volatile phase at the top of the magma chamber (Kent and others, 2007; Rowe and others, this volume, chap. 29), or to a shallow process such as weakening of the conduit cap rock through fracturing induced by late summer rain and glacier melt (Iverson, this volume, chap. 21). In any case, from the perspective of the model, the current eruption is a continuation of 1980s dome building, in which conditions of the magma-plug system differ little between eruptive and noneruptive periods.

Geodetic modeling of GPS data, primarily the long-term record from the receiver at Johnston Ridge Observatory, 9 km from the new lava dome, suggests that the source responsible for deformation is an ellipsoidal body that extends from about 5 km to 10–20 km deep, but that the volume lost from the source is only 20 to 30 percent of the erupted volume of lava (Lisowski and others, this volume, chap. 15). A model that incorporates geodetic and dome-growth data explores possible reasons for this apparent inconsistency, which include ongoing partial recharge, magma compressibility controlled by gas content, and size of the Mount St. Helens magma chamber (Mastin and others, this volume, chap. 22).

Summary

The contributions that follow in this volume represent the work of more than 100 scientists, emergency managers, and information specialists from numerous academic institutions, the USGS, the Gifford Pinchot National Forest, and State and local government. Together they provide a broad perspective of the ongoing eruption of Mount St. Helens and highlight the following events, findings, and lessons learned.

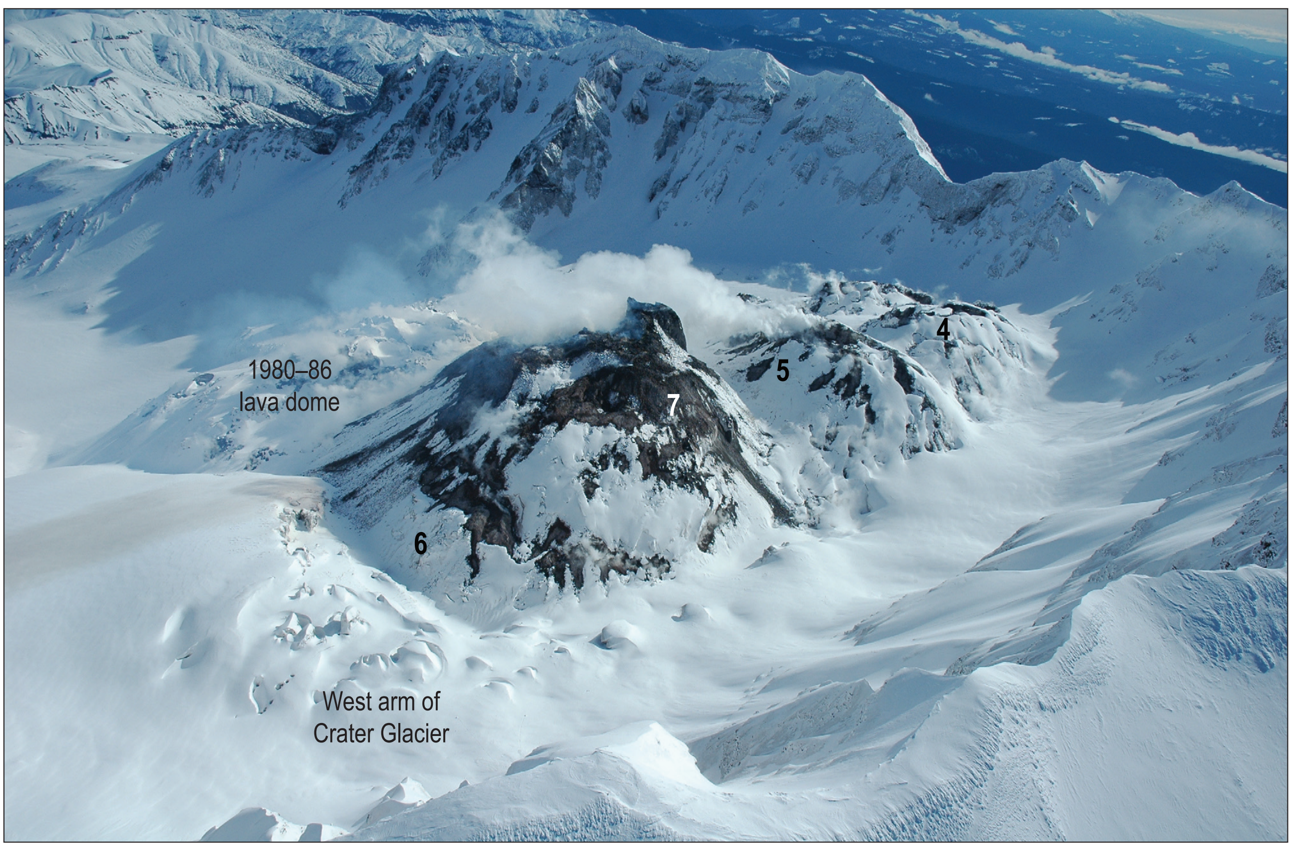

Figure 10. View of Mount St. Helens crater looking east-northeastward taken April 4, 2006. Spines 4 to 7 are identified by numerals; a steeply east-dipping gouge-covered slab of spine 7 (high point) is riding up over earlier parts of spine 7 and spine 6 and pushing them toward viewer's left. At time of photograph, a GPS spider riding to left of numeral 7 was moving about 1 m/d west-northwestward (to left) and slightly downward. Movement of spines 6 and 7 westward was compressing and fracturing west arm of Crater Glacier, but greater-than-normal snowfall during winter of 2005–6 was filling in crevasses and burying much of older part of new lava dome. Shoestring notch, lowest point on the east crater rim, lies just above spine 4. USGS photograph by J.W. Vallance.

The key requirements for successful volcano-crisis response were in place at Mount St. Helens when unrest began on September 23, 2004. These included geophysical monitoring systems, detailed knowledge of the volcano's eruptive history and hazards, a well-trained and highly experienced scientific staff, many public officials and citizens knowledgeable about volcano hazards, and years of close coordination among scientists, land managers, and emergency managers in planning for possible eruptions.

Once volcanic unrest began, intense interest from both media and the public required rapid establishment of a joint information center staffed by scientists and representatives of land-management, emergency-management, and other relevant State and local agencies. The center coordinated dissemination of clear, consistent messages and expanded and shrank as demand dictated.

The 2004-to-present eruption progressed rapidly from unrest to long-term lava extrusion. Between September 23 and October 11, 2004, intense seismic unrest and localized surface deformation, punctuated by four short-lived explosions, constituted a vent-clearing phase. During the final week of this phase, lessened seismicity, minor venting of steam and ash, and rapid localized surface deformation signaled that magma was continuing to push upward through crater-floor debris and glacier ice. Between October 11, 2004, and the present (spring 2006), persistent low levels of small, regular drumbeat earthquakes and sporadic larger seismic events, rare explosions, low gas emissions, and frequent rockfalls accompanied continuous lava-dome extrusion.

Ongoing continuous lava-dome growth has contrasted markedly with the largely episodic growth of the 1980s dome and has resulted in a strikingly different-looking dome. A succession of spines, some recumbent, smoothly gouge-coated, and nearly 500 m long, has built a dome about equal to the volume of the 1980s dome in about one-quarter of the time required to build that earlier dome. Rather than a single mound, the new dome currently comprises three main rock masses arrayed east-west across the crater between the 1980s dome and south crater wall. The vent for extruding lava has remained relatively fixed, and successive spines have been able to push older masses aside across the glacier-covered crater floor.

A dynamical model demonstrates that repetitive stick-slip events, such as drumbeat earthquakes might represent, are an almost inevitable consequence of magma influx at a near-equilibrium rate occurring in conjunction with rate weakening frictional slip along the margins of an extruding solid plug. Because such a condition was attained very early in the eruption, the model implies that the magma-plug system was close to equilibrium at the onset and perhaps needed only a small perturbation to be triggered into action. From this perspective, the current eruption is a continuation of 1980s dome building wherein conditions of the magma-plug system differ little between eruptive and noneruptive periods.

Crystal-rich dacite with a bulk chemical composition similar to that erupted explosively on May 18, 1980, has been building the new lava dome. Some of this is thought to be residual dacite from the 1980s, but a new component is likely admixed. The lava of the current eruption has texture similar to that of the pre-1980 summit dome, which was emplaced over about 150 years. This suggests that the current eruption may last for many more years.

The outcome of the ongoing eruption is uncertain. During the past few thousand years, Mount St. Helens has at times sustained dome growth for more than a century, as during construction of the pre-1980 summit dome; has alternated between explosive and effusive eruptions of dacite; and has also quickly switched from eruptions of dacite to eruptions of lava flows of more mafic composition.

Lava-dome extrusion in a glacier-covered crater has created an unprecedented glaciological experiment. The lava dome bisected the formerly horseshoe-shaped Crater Glacier into two arms that have been successively squeezed against the crater wall and thickened as lava spines bulldozed them outward. The arms were approximately doubled in thickness over a period of months. Flow rates increased, and both termini are advancing vigorously. However, rapid dewatering of glacier beds through the highly permeable crater-floor material has discouraged basal sliding, and most glacier movement consists of internal flow. In addition, extrusion of the lava dome through the glacier has resulted in amazingly little melting.

Localized surface deformation and dome growth, potential hazards to scientists and instruments in proximal areas, and a relatively slow but persistent pace of lava extrusion required development and adaptation of monitoring systems to study the eruption. Low-cost, portable alternatives to traditional GPS and seismic installations, dubbed "spiders," allowed helicopter deployment and retrieval of telemetered instruments in areas on and near the growing lava dome and highly crevassed glacier. Ingenuity combined with the skill of pilots ensured collection of a suite of lava samples from helicopter-borne dredges. Fixed cameras that telemetered images permitted visual observations and repeat images, from which rates of movement could be estimated. DEMs made from a succession of vertical aerial photographs tracked volumetric rates of lava-dome growth and provided detailed bases for a variety of investigations. Throughout the eruption, helicopter-mounted FLIR surveys, a relatively new technique for USGS scientists, provided key information regarding extrusion temperature, vent location, and dome structure.

Update of Recent Activity

Since preparation of this overview and the accompanying volume of reports in 2006, lava-dome growth continued at a slowing rate through 2007 and paused in late January 2008, after more than 39 months of continuous growth. This pause has been characterized by a very low level of seismicity, cessation of ground-tilt events that were discernible on shallow-borehole tiltmeters installed in late 2005 and summer 2006, and barely detectable efflux of sulfur dioxide. Analysis of repeat photographs from fixed cameras shows no evidence of extrusion, but rather only movement indicative of gravitational settling of spine 7, which is confirmed by a GPS spider atop the spine. As a result of these observations, USGS–CVO reduced the alert level to Volcano Advisory/Aviation Color Code Yellow on February 21, 2008, to signify that volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase. (As noted in table 1, the unified notification system adopted by all USGS volcano observatories in 2006 uses some new terms and redefines others from the system in use in 2004. Advisory/Yellow under the new system is roughly equivalent to Notice of Volcanic Unrest/Yellow in the old system).

From 2006 to early 2008, spine 7 continued to broaden. By July 2007, the new lava dome was slightly more than 1 km long (axis west-southwest to east-southeast) and about 0.6 km wide. Extruded volume had reached about 93×10^6 m^3, and average extrusion rate had dropped from about 0.5 m^3/s during 2006 to 0.1–0.2 m^3/s (S.P. Schilling, oral commun., 2007). Seismicity gradually diminished through 2006–7 and remained shallow (S.C. Moran, oral commun., 2007), the craterward motion of GPS instruments slowed greatly and probably ceased by mid-2007 (M. Lisowski, oral commun., 2007), gas emissions have remained at low levels (K.A. McGee, oral commun. 2007), and the composition of the erupting dacite remains unchanged from that reported in the first 2004 samples (Thornber and others, 2008b). No explosions have been detected since March 2005. Rockfalls and rock avalanches have continued, but the lack of high, steep fins and crags since autumn 2006 has kept their volume small. The arms of Crater Glacier continue to advance, the west arm most rapidly. As of February 2008, the snouts of the arms had touched, thereby enveloping the 1980–86 lava dome. Whether this pause in extrusion in early 2008 signals the end of dome growth or signals the start of a period of episodic lava extrusion, as happened in the 1980s, will become evident during the coming months to years.

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